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Geotechnical and geomechanical aspects of pillar optimization on weak soil using Numerical Methods

Bachelor Thesis

By

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Ulaanbaatar/Nalaikh, 5/18/2023
Place, Date

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Abstract

Room and pillar mining is an established method used worldwide to extract coal, salt, and other minerals. Which method widespread use can be attributed to its relatively low cost, safety, and versatility in various geological conditions. The geotechnical and geomechanically aspects of optimizing pillars on unstable soil present mining engineers with significant challenges. It is essential to optimize pillars for the stability of underground mining operations. However, it is difficult to accurately foresee the behavior of weak soil and the surrounding rock mass due to its unique properties. Numerical methods can resolve these challenges by simulating the soil and rock mass behavior and assessing the pillars' stability.

This paper utilizes numerical modeling in FLAC3D to investigate ways to optimize mining methods considering economic and safety aspects. It also aims to determine the stability of pillars in soft rock. To achieve this, the study examines the increasing use of backfilling in underground mining, driven by the need for systematic backfilling of mine openings and workings for mine technical, environmental, and economic reasons. Mining operations can achieve greater efficiency while improving safety and reducing environmental impact by optimizing mining dimensions and utilizing backfilling techniques.

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m	Meter	ϵ	Strain
kg/m^3	Kilogram per cubic meter	τ	Shear strength
MPa	Megapascal	σ_n	Normal stress
GPa	Gigapascal	Sp	Pillar strength
σ	Uniaxial stress	w	Pillar width
E	Young's Module	h	Pillar height

1. INTRODUCTION

1.1. Background and objective of the study

The risk of collapse and danger to underground workers is a significant concern in room and pillar mining under weak rock conditions. Proper geotechnical and geomechanical research can protect the stability of underground mining operations, leading to potentially catastrophic consequences. Pillar optimization is crucial for ensuring underground mining operations' stability, but weak soil's unique properties present significant challenges to mining engineers. Accurately predicting the behavior of the soil and the surrounding rock mass can take time, making it challenging to optimize the pillars effectively.

Numerical methods can help address these challenges by simulating the soil and rock mass behavior and assessing the stability of the pillars. However, accurately modeling the behavior of weak soil requires advanced numerical modeling techniques, including non-linear elastic material models and accounting for the effects of discontinuities such as joints and faults. It is essential to calibrate these numerical models to ensure they accurately predict the stress-strain and failure behavior of the rock mass, allowing accurate predictions of pillar stability.

Balancing mining operations' economic and safety aspects is critical, and pillar optimization research must consider both factors. By optimizing the pillars and ensuring worker safety, mining companies can maximize their profits while minimizing the risks associated with underground mining.

Therefore, geotechnical and geomechanical research is crucial for safe and efficient room and pillar mining operations under weak rock conditions. By using advanced numerical modeling techniques, engineers can accurately predict the soil and rock mass behavior, optimizing the pillars to ensure stability while balancing economic considerations. Proper pillar optimization can help prevent collapse and ensure worker safety, allowing for underground mining operations' safe and profitable operation.

1.2. Research Questions

This paper raises three main research questions with one sub-question each.

- How can we optimize the pillar design in weak rock conditions by using numerical methods?
- How do various geotechnical and geomechanical factors affect the stability of underground openings in room and pillar mining?
- How can we ensure the right balance between safety and economic aspects while optimizing the mining method in weak rock conditions?

1.3. Significance of the study

The significance of my study lies in its contribution to the field of geotechnics and geomechanics, specifically in the area of underground mining on weak rock. By using numerical methods, my research will provide new insights and knowledge on the optimization of pillars in room and pillar mining, which can ultimately improve safety and efficiency in underground mining operations.

Furthermore, my study can serve as a foundation for future research and development in this field in Mongolia and beyond. As the mining industry continues to grow and expand, the demand for innovative and effective techniques for optimizing underground mining operations will only increase. My thesis can therefore play a crucial role in shaping and advancing the future of mining engineering research and practice.

1.4. Research objectives

The thesis aims to:

- Numerical modeling of a mining scheme
- Investigation of safety aspects of the mining scheme
- Investigation of how to optimize the mining method under economical and safety aspects

- Geotechnical and geomechanically research is the key to safe mining operations

1.5. Limitations of the study

This study focuses on the geotechnical and geomechanical aspects of pillar optimization in room and pillar mining under weak rock conditions using numerical methods. The goal is to develop a model for room and pillar mining and investigate how to optimize the mining method, focusing on safety and economic considerations. The study will not include hydrogeological aspects water management, ground support, and monitoring in detail. It is important to note that the study does not include an analysis of specific geological properties or authentic mining schemes. Instead, the study uses numerical simulations to optimize pillars in the context of weak rock conditions. Therefore, this study's findings may have limited applicability to real-world mining operations that differ significantly in their geological properties and mining methods. Further research is needed to investigate the specific geological properties and mining schemes of different sites and apply pillar optimization principles to these specific conditions.

1.6. Workflow of the study

First, a thorough understanding of the geological and geomechanical properties of the deposit is needed. This is usually achieved through geotechnical and geomechanical investigations, and laboratory testing, which is used as input for numerical modeling. However, this is beyond the scope of a Bachelor thesis. My research is based on geological information from textbook and articles that are similar to real geology.

Next, the pillar design and mining sequence need to be optimized based on the results of these investigations, considering both economic and safety aspects. Numerical methods can be used to simulate different mining scenarios and assess their stability and economic viability.

Ultimately, the investigation should aim to identify the most efficient and safe mining method for the specific weak soil deposit, considering the available resources and constraints. This will lead to improved mining operations and at the time to minimized risks for underground workers.

2. LITERATURE REVIEW

2.1. Room and Pillar Mining

Room and pillar mining is a method of underground mining commonly used to extract coal, potash, salt, or other minerals deposited in seams or veins. This method excavates tunnels or "rooms" into the seam, leaving behind "pillars" of the mineral or rock to support the roof. Figure 1 shows a plan view of an idealized room and pillar mine. The square blocks are pillars; the spaces between the pillars are rooms. The pillars are typically arranged in a regular grid pattern, with the size and shape of the pillars being determined by the strength of the surrounding rock, taking into account the desire extract as much material as possible. In hard rock, pillars are usually much smaller horizontally than rooms. In soft rock, they are usually much larger because of the stability aspects.

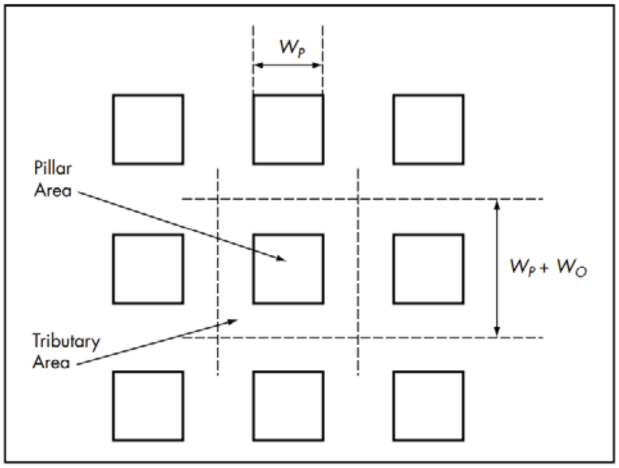


Figure 1: Idealized Room and Pillar mining structure

The process of room and pillar mining involves several steps. First, a network of tunnels is excavated into the seam, e.g., using drilling and blasting techniques. To prevent collapses, the tunnels are then supported with roof bolts, steel mesh, or other support systems. Next, the coal or mineral is extracted from the seam. The pillars are left intact to support the roof and prevent cave-ins.

One advantage of room and pillar mining is that it can be used in relatively shallow deposits. It is a flexible method that can be adapted to different geologic conditions and mining environments. However, the method has some disadvantages, such as lower recovery rates compared to other mining methods and the need for additional support systems to prevent roof collapses.

In recent years, technological and equipment advances have improved the efficiency and safety of room and pillar mining. For example, remote-controlled machines and automated systems can now be used to excavate tunnels and extract minerals, reducing the need for human labor and increasing safety. Additionally, new support systems such as rock bolts and shotcrete can provide increased stability to the mine workings. The support systems come with a cost and will have an impact on the economic aspects.

2.2. Weak rock mining

Weak rock mining involves extracting materials from geological formations with relatively low strength, such as sedimentary rock, coal, or salt. This type of mining can be conducted through underground methods like room and pillar or longwall mining or surface mining methods like strip or open-pit mining. While soft rock formations are easier to excavate, they also pose challenges for stability and ground control in underground mining and for maintaining the stability of overlying soil or rock in surface mining.

Room and pillar mining under weak rock conditions presents significant challenges, as the rock mass surrounding the excavated rooms may need more support. To address this issue, modifications to the mining design can be employed, such as smaller room sizes and larger pillar sizes and using ground support measures like bolts, mesh, and shotcrete. Groundwater infiltration can also weaken the rock mass, making dewatering and drainage systems essential for managing potential instability. Successful room and pillar mining in weak rock conditions requires careful consideration of geotechnical properties and appropriate ground support measures to ensure safety and stability.

2.3. Geotechnical aspect

Geotechnical aspects ensure the stability and safety of structures built on or in the ground. By understanding the properties of the rock, the groundwater movement, slope stability, seismic activity, climate and weathering, and ground movement and settlement, mining engineers can develop appropriate design and construction techniques to mitigate potential risks and hazards. Proper consideration of geotechnical aspects can minimize the risk of failure, reduce construction costs, and extend the lifespan of infrastructure.

2.3.1 Geotechnical aspect on weak rock condition in Room and Pillar mining

In weak rock conditions, geotechnical aspects play a critical role in the design and operation of room and pillar mining. Some of the critical geotechnical aspects to consider include the following:

1. Rock mass properties: The strength and stability of the rock mass surrounding the excavated rooms are essential factors in determining the stability of the mine workings. In weak rock conditions, the rock mass may not support the weight of the overlying strata, resulting in roof collapses and other stability issues. Therefore, it is essential to analyze the rock mass properties, including its strength, deformation behavior, and fracture characteristics.
2. Support: Ground support measures, such as bolts, mesh, backfill and shotcrete, can support the rock mass and prevent roof collapses. The selection and design of ground support measures should consider the rock mass properties, the size and shape of the excavations, and the loading conditions.
3. Pillar design: In room and pillar mining, pillars are left to support the roof. Under weak rock conditions, it may be necessary to increase the size of the pillars to provide additional support. The size and spacing of the pillars should be designed to ensure the stability of the mine workings while minimizing the mining losses.

4. Water management: Groundwater can weaken the rock mass and increase the risk of roof collapses. Effective water management, including dewatering and drainage systems, can help manage groundwater and reduce the risk of instability.
5. Monitoring: Monitoring the mine workings is essential in weak rock conditions. Monitoring systems, including geotechnical instrumentation, can provide early warning of stability issues and help inform ground support and pillar design decisions.

By considering these geotechnical aspects, engineers can design an operating room and pillar mining in weak rock conditions safely and efficiently.

2.4. Geomechanical aspect in room and pillar mining

Geomechanical analysis is a crucial aspect of geotechnical engineering that involves examining the physical properties of geological materials, such as their strength, deformation characteristics. This analysis is used to design the mining operations, including drifts, pillars support, that can withstand the pressures of the surrounding geological materials. The importance of geomechanical analysis is not limited to mining and civil engineering but extends to petroleum and environmental engineering. The knowledge gained from the geomechanical analysis is used to design and operate structures and wells that can withstand high pressures, temperatures, and natural disasters in their respective fields. Overall, geomechanical analysis plays a critical role in ensuring infrastructure projects' safe and efficient operation.

2.4.1 Geomechanical aspect on Room and pillar mining

The geomechanical aspect is essential in designing and operating room and pillar mining. It involves studying and analyzing the mechanical behavior of the rock mass surrounding the excavated rooms and the stability of the pillars left in place to support the roof.

One of the primary geomechanical concerns in room and pillar mining is the stability of the rock mass surrounding the mined-out areas. Various factors, including the rock's strength and stiffness, the rock's orientation of joints and fractures in the rock mass, and the stress regime within the rock mass, influence the stability of the rock mass. Understanding these factors is essential in determining the appropriate size, shape, and spacing of the excavated rooms and the pillars left in place to support the roof.

Another important geomechanical aspect of room and pillar mining is the deformation behavior of the rock mass. The rock mass is subjected to deformations, and tensile and shear failure. The deformations and the failure of the rock mass will impact the stability of the pillars and the roof and the overall stability and therefore safety of the mining operation. Therefore, the deformation behavior of the rock mass is carefully analyzed to ensure the stability of the mine opening and the safety of the workers.

2.4.2 Geomechanical properties of weak rock

Geomechanical properties of weak rocks are those physical and mechanical properties that affect the response of the rock to external forces, such as stress and strain. Examples of Geomechanical properties of (weak) rocks include elastic properties (bulk and shear modulus) and strength parameters (tensile strength, cohesion and friction, dilatancy) behavior. These properties will influence the behavior of weak rocks under various loading conditions, including mining-induced stresses and strains. Understanding the geomechanical properties of weak rocks is essential in designing effective and safe mining practices in such conditions.

2.5. Numerical Model

Numerical modeling is a technique used to simulate real-world phenomena or processes by using mathematical models. It involves using computer software to simulate the stress-strain behavior and the failure mechanisms of a complex system.These models can be used to predict how the system will behave under different conditions, optimize the system's performance, and better understand how the system works. For achieving this, a calibration of the model (and its properties) is needed.

Numerical modeling is used in various fields, including physics, engineering, environmental science, and finance. It is beneficial when it is difficult or impossible to conduct experiments in the real world, such as in the case of natural disasters, climate change, or complex engineering systems. In these cases, numerical modeling provides a cost-effective and efficient way to study the system and predict its behavior.

2.5.1 Numerical modeling in geotechnical and geomechanical in mining

In geotechnics and geomechanics, the numerical model has a critical role. Numerical modeling is widely used in mining engineering. The behavior of rock masses and the interactions between the ground and mining structures can be complex and highly variable, making it challenging to predict and optimize mining operations.

Numerical modeling allows mining engineers to simulate and study these systems under different conditions, optimize mining methods, and identify potential safety hazards.

In geotechnics, numerical modeling is used to analyze underground excavations' stability and design support systems such as backfill, rock bolts and shotcrete. For example, a mining engineer may use numerical modeling to predict the deformation and failure of the surrounding rock mass during excavation and to optimize the placement of support structures to minimize the risk of rockfall or other types of failure. Numerical models can also be used to simulate the behavior of rock masses during blasting to minimize the risk of damage to the surrounding rock and structures.

In geomechanics, numerical modeling is used to simulate the behavior of rock masses during mining, including the deformation and failure of rock structures under different loading conditions. For example, a mining engineer may use numerical modeling to predict the behavior of a rock mass during a mining operation, optimize the extraction method, and minimize the risk of instability or collapse. Numerical models can also be used to design and optimize the layout of underground mining infrastructure, such as drifts, shafts, and ventilation systems.

Overall, numerical modeling is a critical tool in mining engineering, enabling researchers and engineers to better understand and optimize complex systems' behavior in geotechnics and geomechanics. By simulating and studying these systems, researchers can identify potential problems or areas for optimization, leading to safer and more efficient mining operations.

2.5.2 Numerical modeling on room and pillar mining

FLAC3D (ITASCA international Inc.) is a highly regarded numerical modeling software program used extensively in the fields of geotechnics and geomechanics. FLAC3D means Fast Lagrangian Analysis of Continua in 3 Dimensions. This software offers sophisticated capabilities to simulate the behavior of geological materials in three dimensions using the finite difference method. It is used to analyze and study various aspects of geotechnical engineering, including the behavior of soil, rock, groundwater, and ground support structures. It is capable of performing engineering design, predicting the factor of safety for different scenarios, conducting research and testing, and analyzing failures retrospectively. In essence, it provides a powerful tool for mining engineers to better understand the complex geomechanical aspects of mining operations and to optimize their design for safety and efficiency.

FLAC3D™

In room and pillar mining, FLAC3D can be used to simulate the behavior of the rock mass during excavation, the stability of the pillars and the potential for roof collapse. Such information can be used to optimize the design of the mining layout, the size and shape of pillars and the sequence of panel extraction.

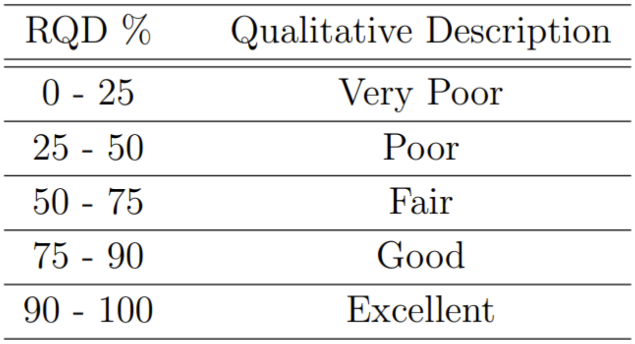
FLAC3D provides a valuable tool for mining engineers to better understand the complex geotechnical and geomechanical aspects of room and pillar mining and to optimize their design for safety and efficiency. By modeling different scenarios, engineers can gain insights into the behavior of rock masses and develop strategies to minimize the risk of ground failures, seismic events, and other hazards.

2.6 Rock mass classification

Rock mass classification systematically categorizes rock masses into groups based on their geological and engineering characteristics. It evaluates various parameters such as rock strength, mass structure, joint spacing, and water content. Rock mass classification aims to quantitatively characterize rock mass behavior and predict its response to engineering activities. Rock mass classification systems are used in various fields, including mining, tunneling, and slope stability analysis, to assist in design decisions and risk assessments. Some commonly used rock mass classification systems include the RMR (Rock Mass Rating) and RQD (Rock Quality designation).

2.6.1 Rock Quality Designation

One of the oldest rock mass classification systems, still widely used today, is the rock quality designation (RQD) system. In 1966 Don Deere described the RQD system, designed to quantify the percentage of recovered core quantitatively. Rock quality designation (RQD) measures the quality of rock core samples obtained through drilling. RQD is calculated as the percentage of intact rock length within a core sample length. The length of intact rock is defined as pieces longer than 10 cm, unaffected by significant fractures or weakness planes. RQD values are used to evaluate the rock mass quality and determine its suitability for engineering purposes. Higher RQD values indicate a more competent and stable rock mass, while lower values suggest a weaker and less stable rock mass. RQD is a widely used parameter in geotechnical engineering for slope stability analysis, foundation design, and tunneling.



RQD %	Qualitative Description
0 - 25	Very Poor
25 - 50	Poor
50 - 75	Fair
75 - 90	Good
90 - 100	Excellent

Table 1: Qualitative descriptions of rock quality designation ranges as suggested by Deere.

2.6.2 Rock mass rating

The Rock Mass Rating System is the one rock mass classification system to include RQDs as part of several parameters. The original name for the RMR system, which Bieniawski developed, is Geomechanics Classification. Rock Mass Rating (RMR) is based on six parameters to calculate an overall RMR value. These parameters include the uniaxial compressive strength of the rock, the rock quality designation (RQD), the joint spacing and orientation, the condition of the joint surface, the groundwater conditions, and the slope orientation. The RMR system assigns a numerical value to each parameter and calculates an overall RMR value that ranges from 0 to 100. The higher the RMR value, the better the quality and stability of the rock mass. RMR is commonly used in geotechnical engineering for slope stability analysis, tunneling, and foundation design.

Rating	Class no.	Qualitative Description
100 - 81	I	Very Good Rock
80 - 61	II	Good Rock
60 - 41	III	Fair Rock
40 - 21	IV	Poor Rock
< 20	V	Very Poor Rock

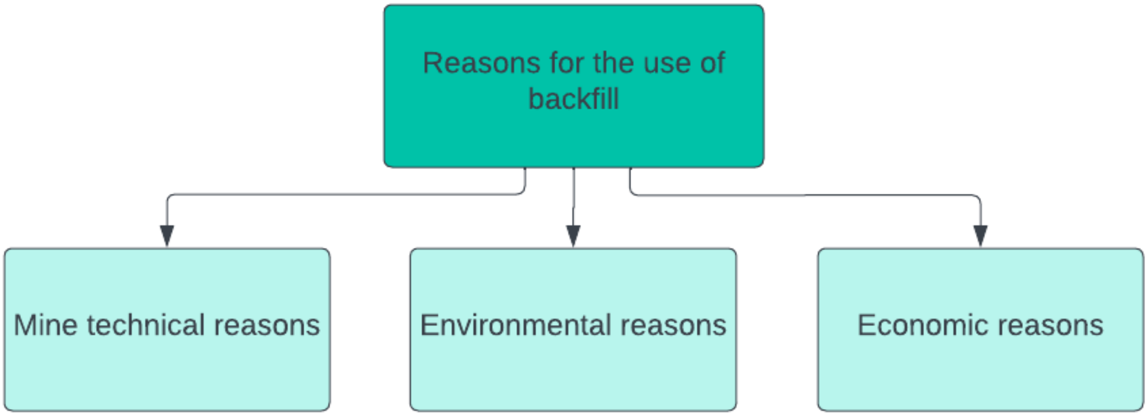
Table 2: Qualitative description associated with rock masses with RMR ranges as suggested by Bieniawski

Class no.	Average stand-up time	Cohesion (kPa)	Friction Angle (°)
I	20 yr for 15-m span	> 400	> 45
II	1 yr for 10-m span	300 - 400	35 - 45
III	1 wk for 5-m span	200 - 300	25 - 35
IV	10 hr for 2.5 -m span	100 - 200	12 - 25
V	30 min for 1-m span	< 100	< 15

Table 3: Quantitative estimates of rock mass strength parameters, rock mass cohesion, rock mass friction angle, and the expected life of a tunnel through a rock mass based on rock mass rating ranges as suggested by Bieniawski

2.7 Backfilling

There is a growing demand for the methodical backfilling of mine entrances and workings, which is driving an increase in the utilization of backfill in underground mining. The term "backfill" refers to the substance or materials utilized in underground mines' void openings for mining technical or mining safety. Backfill can be described as the material or materials that are used. Backfill is added to prevent collapse and explosions, enhance mine ventilation, strengthen the rock's stability, lessen the consequences of subsidence at the surface, and for a variety of other reasons, including those related to the economy, mine technical and the environment.



The backfilling process is carried out for several purposes, including mine technical, environmental, and economic concerns.

Mine Technical Reasons:

Stabilizing mine openings and reducing the risk of subsidence are the technical reasons for backfilling. Backfilling helps prevent the collapse of underground constructions, in which the weight of the overlying rock or water pressure can cause the weight of the overlying rock or water pressure. This technique assists with creating a stable working platform for miners and reduces the quantity of material that must be transported out of the mine.

Environmental Reasons:

Among the environmental benefits of backfilling are subsidence prevention, surface protection, and air pollution. If waste is left on the surface, it can be eroded and contaminate adjacent water sources. Backfilling helps prevent erosion and can also help contain mine contaminants. And backfilling can prevent the release of dust and other air pollutants, enhancing air quality.

Economic Reasons:

Reducing deposit loss, averting ore dilution, and minimizing dumping or reclamation costs are economic reasons for backfilling. When refuse is left in a mine, valuable minerals may be lost, and Backfilling ensures that all valuable minerals are extracted. Backfilling can also prevent ore dilution, reducing the extracted minerals' total value. Last but not least, backfilling can reduce the need for depositing waste material on the surface or for costly reclamation activities after mining has been completed, thereby reducing overall costs.

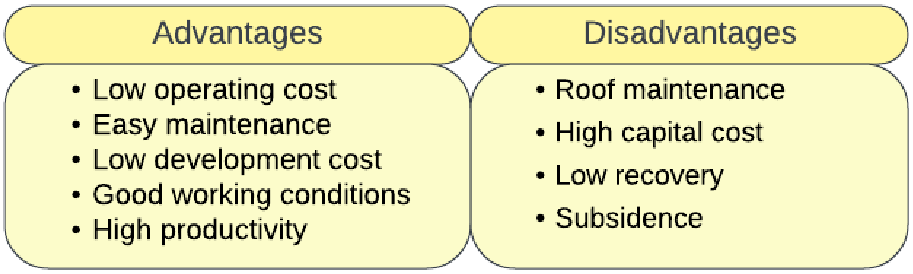
2.7.1 Geomechanics of Backfill

Geomechanics of backfilling refers to the mechanical behavior of backfill within a mining pillar. Understanding the physiochemical properties of backfill constituents is crucial in optimizing backfill design for maximum quality and minimum cost in mining operations. The selection of backfill materials should be based on the engineering properties and compaction characteristics of the materials available. The results of field exploration and laboratory test programs should provide adequate information for this purpose. The mechanical and cure properties of backfill placed underground may change remarkably depending upon the intrinsic properties of the material, method of preparation, placement, and mine environment conditions. Thus, engineers must carefully consider these factors when designing and implementing backfilling operations to ensure their success and safety.

The Geomechanics of backfilling plays a critical role in successful and safe mining operations. During my study, based on weak rock conditions, thus my backfill strength would be high because appropriate backfill materials and proper placement techniques are essential in optimizing backfill design and minimizing mining costs. Engineers must carefully consider the physiochemical properties of backfill constituents, their interactions, and the mine environment conditions to achieve maximum quality and safety.

2.8 The economic aspect of weak rock in a room and pillar mine

Typically, mining operations are motivated by the maximization of profits. Nonetheless, it is crucial to acknowledge that mining activities can significantly impact both safety and the environment. The economic impact of weak rock in a room and pillar mine can be significant.



Advantages	Disadvantages
Low operating cost	Roof maintenance
Easy maintenance	High capital cost
Low development cost	Low recovery
Good working conditions	Subsidence
High productivity	

Room and pillar mining is cost-effective with low operating and development costs. However, it also shows that the method has high capital cost.

Therefore, mining engineers should concentrate on enhancing ground support, and pillar size, implementing backfilling, and adjusting the mining method to enhance profitability and guarantee the mine's sustainability over the long run. Geological data is kept the same since it takes millions of years to form. The room and pillar mining operations consider the balance between economic and safety considerations. From an economic and safety side, optimizing the dimensions of the pillars and rooms is important. Backfill material must be carefully selected and placed to adequately support the pillars and prevent deformation or failure.to ensure that the maximum amount of ore can be extracted while minimizing the cost of the operation. Based on weak rock conditions, the backfill should be strong enough to hold the weight of the rocks on top and keep the structure from falling. It should also be flexible enough to move with the ground and keep the pillars from getting damaged. Besides, the pillar sizes would be larger than strong rock conditions.

3. METHODOLOGY/MODEL DEVELOPMENT

The main objective of this thesis is to examine the initial response of the excavation under in-situ stresses and subsequently determine the maximum load the pillars can withstand. The elastoplastic behavior of the rock in and around the mining zone is modeled using the Mohr-Coulomb constitutive model. By creating well-calibrated numerical models, it is possible to gain insight into the load and failure mechanisms in the mined-out region. The research focuses on numerical modeling and employs an elastoplastic constitutive model. Parametric studies are conducted using the FLAC3D finite difference software, with a focus on weak geology conditions that are graded.

3.1. Mechanics overview

When external forces are applied, stress is formed inside a deformable body. The stress generated is proportional to the applied. Normal stresses act perpendicular to the region on which they operate, whereas shear stresses act parallel to the area on which they act. In three dimensions, an element's total state of stress inside a deformable body includes the nine stresses shown as arrows in Figure 2.

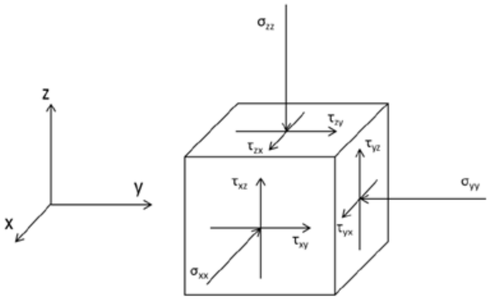


Figure 2: A three-dimensional element with all stress components depicted

3.1.1 Elastic module

Constitutive models, describe the stress-strain behavior of a material. To describe the deformation of a material under stress, the simplest constitutive model assumes that the material deforms proportionally to the load applied. It is similar to the statement that stress and strain are linearly related. The following Equation describes the elasticity model.

$$\sigma = E\epsilon$$

Equation 1: Elasticity module

Here E is known as the Young’s modulus. Figure shows the relationship in graphical form The slope of the stress-strain curve of an elastic material is constant and equal to Young’s modulus of the material. Moreover, elastic materials shall be used for the recovery of strain when they are unloaded. The elastic strain does not cause permanent deformation.

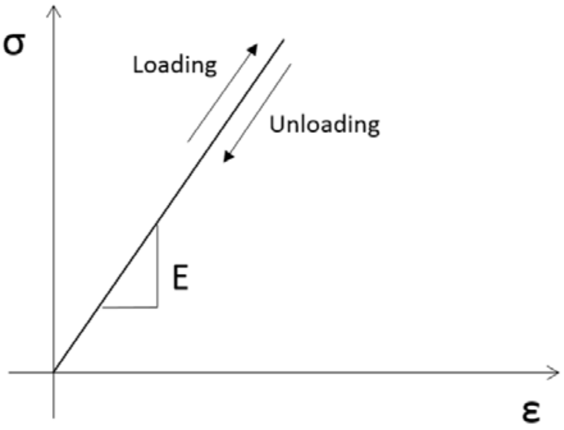


Figure 3: Stress-Strain curve of elastic loading and unloading

The axial stress is related to the axial strain by the young modulus. The deformation of material in the same direction is caused by an axial strain. Figure 3 shows this phenomenon referred to as the Poisson effect. While the amount of elongation, ∆L, due to the extensional stress in Figure 3 is dictated by Young's modulus, the degree to which that elongation causes Poisson's ratio describes the narrowing of the member.

$$\nu = -\frac{\epsilon_{lateral}}{\epsilon_{axial}}$$

Equation 2: Poisson's ratio

where $\epsilon_{lateral}$ is the lateral strain and $\epsilon_{axial}$is the axial strain. Almost all materials are subject to a positive axial strain extension, as opposed to an adverse axial strain composition and negative axial strain. To make the Poisson's ratio generally positive, the ratio shall be nullified.

3.1.2 Plastic Strain

Plastic deformation is a phenomenon in materials science that describes the irreversible deformation of a material under the application of an external force. This type of deformation can occur in materials subjected to stress levels beyond their yield point. The yield point is the stress level at which the material begins to deform plastically. In other words, plastic deformation occurs when the stress on a material exceeds its yield strength, resulting in permanent or non-elastic deformation. The elastic, perfectly plastic model is widely used for plastic deformation analysis in materials science. This model assumes that, until the material reaches its yield point, it will behave elastically, returning to its original shape once the external force is removed. Once the yield point is reached, the material will deform plastically while maintaining a constant stress level at yield strength. This means that the material will continue to deform plastically without any increase in stress until it reaches its ultimate strength, where it will eventually fracture.

The elastic, perfectly plastic model is an idealized model frequently used to describe the behavior of metals and other materials undergoing plastic deformation. It provides a good approximation of the deformation behavior of many materials, although it may only sometimes be accurate for all materials.

3.2 Failure Criterion

To design real structures, it is crucial to understand the strength characteristics of the rock in its natural state. The most common method to determine rock strength is through laboratory tests, usually conducted on small samples of intact rock. Reduction factors are typically applied because the validity of lab test results on intact rock samples cannot be assumed for non-intact rock.

The Mohr-Coulomb and the Hoek Brown failure criteria are two of the most commonly used methods to estimate rock strength. Through constitutive models, relationships between stress and strain are expressed. To describe the deformation of a material under stress, the simplest constitutive model assumes that the material deforms proportionally to the load applied. It is similar to the statement that stress and strain are linearly related. Shear strength and applied normal stress are linearly related according to the Mohr-Coulomb failure criterion. The Hoek-Brown failure criteria were developed in the 1980s using an equation developed by Evert Hoek and Edwin Brown to determine the strength of concrete while evaluating rock. The intermediate primary stress, demonstrated to have a significant and predictable impact on failure, is ignored by both failure criteria despite being the most frequently utilized design constraint in rock mechanics.

3.2.1 Mohr-Coulomb failure criterion

The Mohr-Coulomb failure criterion is a popular model for predicting rock failure under compression due to its simplicity, ease of understanding, and accuracy across various loading conditions. Due to its reliability and practicality, it remains one of the most widely utilized methods for forecasting rock failure.

The critical value is a function of the normal stress acting on the same plane, as well as the material's internal friction angle and cohesion. The Mohr-Coulomb failure criterion is commonly used in geotechnical engineering to analyze the stability of slopes, tunnels, and other excavations in soil and rock masses.

As shown in Equation, the Mohr-Coulomb failure criterion predicts the shear strength, $|\tau|$, to be a function of the applied normal stress, σ_n.

$$|\tau| = \sigma_n tan\phi + c$$

Equation 3:Mohr-Coulomb failure criterion

where ϕ and $c$are empirically derived parameters. The parameter φ is called the angle of internal friction, and c is cohesion. The angle of internal friction can oppose sliding due to the product of it and normal stress, while cohesion can prevent failure in cases of pure shearing.

3.2.2 Hoek-Brown failure criterion

An empirical relationship to predict failure, which is nonlinear, is provided by Hoek-Brown's failure criterion. The equation showed the relationship to be originally developed as follows: Strength criterion for concrete, but Hoek and Brown have adapted it in order to describe rock failure.

Hoek and Brown proposed the new relationship because it is the first rock failure criterion that can be applied to intact rock for any stress conditions expected underground, handle the presence of joint sets, and provide insight into rock mass response.

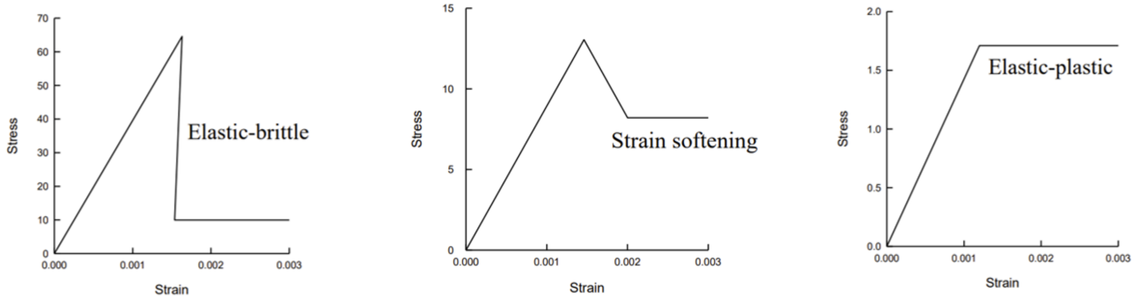
$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}$$

Equation 4: The Hoek-Brown failure criterion supplies an empirical relationship for predicting failure

Where $\sigma_1$is the maximum principal stress at failure, σ_3 is the minimum principal stress, σ_c is the uniaxial compressive strength of intact rock, and m and s are empirically derived material constants.

3.2.3 Post-Failure behavior

The post-failure characteristics of a rock mass play a crucial role in underground excavations' design and stability analysis. Three common post-failure characteristics for different quality rock masses are elastic brittle, strain softening, and elastic plastic.



(a) Very good quality hard rock mass (b) Average quality rock mass (c) Very poor quality soft rock mass

Figure 4:Suggested post failure characteristics for different quality rock masses

Elastic brittle rock masses fail suddenly with minimal post-peak deformation, typical of hard and intact rock masses. Strain-softening rock masses experience a reduction in strength and stiffness due to cracking and fragmentation, and a significant drop in the stress-strain curve characterizes their post-failure behavior. Elastic-plastic rock masses exhibit significant post-peak deformation while retaining some residual strength, typically observed in softer and more ductile rock masses. To maintain stability and prevent further deformations, different ground support measures such as rock bolts and shotcrete, mesh and cable bolts, and bolts, reinforcement, and backfilling may be required for elastic brittle, strain softening, and elastic-plastic rock masses, respectively.

3.3 Design of Underground openings

3.3.1 Pillar stability

Due to the lack of high-capacity testing facilities, it is not easy to accurately assess a pillar's strength in this field. A typical power equation is used for calculating pillar strength *Sp*, which can be expressed as a function of the width-to-height ratio of a pillar and a constant:

$$Sp = k \cdot w^{\alpha} \cdot h^{\beta}$$

Equation 5: Power equation for pillar strength

The formula consists of four variables: pillar width (w), pillar height (h), two constants (α and β), and a constant (k) that represents the strength of the material.

The Bieniawski formula is important in room and pillar mining as it provides a means to calculate the stability factor of the pillars. This allows the design and selection of appropriate pillar dimensions based on the strength of the weak rock condition. Using the Bieniawski formula, engineers can ensure the safety and stability of underground mining operations. The pillar strength is Sp, of a square pillar as given by the Bieniawski formula is

$$Sp = \ Si\left(0.64 + 0.36\frac{w}{h}\right)$$

Equation 6: Bieniawski equation

Where Hp is the pillar height, and Wp is the pillar width.

Factor of safety

The stability assessment of mine pillars is conventionally carried out using deterministic approaches, such as empirical or analytical methods. These methods usually involve using a safety factor (SF) to evaluate the stability level of the pillar.

For the stability of pillars, a safety factor is taken into account when designing columns. In many cases a strength stress ratio can be displayed as follows:

$$SF = \frac{Strength}{Stress} = \frac{Sp}{\sigma p}$$

Equation 7: Safety factor

Here safety factor is SF and the variables are Sp and σp in a probabilistic approach. Calculating the factor of safety is a simple process in most cases, and the results are easily understandable. When a component or structure has a higher strength than the expected stress, the safety factor will larger than 1. The higher SF value, the lower the risk of failure. If the stress applied to a component or structure surpasses its strength, the safety factor will be below one, and failure is anticipated.

3.3.2 Geomechanical property of rock

The essential geomechanical characteristics of rock comprise its density, Young's modulus, cohesion, tensile strength, Poisson's ratio, and angle of internal friction. These parameters are crucial in determining the rock's behavior and response to mechanical and external forces, providing insight into its overall strength, stability, and durability.

Young’s Moduluse

Young's moduluse, also called the elasticity modulus, is a mechanical characteristic that quantifies the rigidity of a solid substance. It is defined as the ratio of stress (force per unit area) to strain (change in length per unit length) in a linear elastic deformation regime. It defines how the tensile or compressive stress σ (force per unit area) is related to the axial strain ε (proportional deformation) in the linear elastic region of a material, and it can be calculated using the equation:

$$E = \frac{\sigma}{\varepsilon}$$

Equation 8: Young’s Modulus

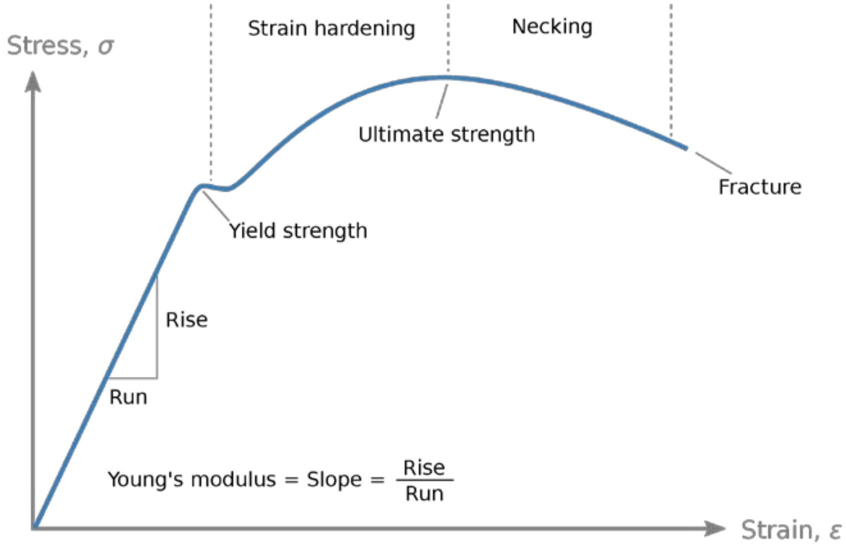


Figure 5: For a material under tension or compression, the Young's modulus is the slope of the linear part of the stress curve

According to this figure, A material with a high Young's modulus value will have a higher resistance to deformation under stress and, therefore, can withstand needs higher stress to undergoing significant deformation.

Cohesion

Cohesion is a fundamental concept in geology that describes the ability of a material, such as soil or rock, to resist being pulled apart or sheared due to the internal forces between its particles. It measures the intermolecular forces that hold the particles together and is influenced by various factors, including particle size, shape, surface texture, and the material's chemical and physical properties. The cohesion of a material is an essential factor in determining its strength and stability, particularly in geotechnical engineering applications where soil and rock mechanics are critical for construction and infrastructure projects.

Friction angle

In rock mechanics, the friction angle (ϕ) comprises the primary friction angle (ϕ_b) of the rock and the dilation angle caused by the roughness of the joint, which together determine the resistance to shear along the plane of the joint. The friction angle is dominating property for the shear behavior, once the shear forces overcome the cohesion.

The frictional angle of the rock is a function of its size and shape as well as that of the grains exposed on the fracture surface. Therefore, the friction angle is low for fine-grained rock, whereas the friction angle is high for coarse-grained rock.

Poisson’s ratio

The Poisson's ratio is a significant material science and engineering mechanics parameter. It describes the relationship between the changes in a material's transverse and axial directions when applied force. This phenomenon is called Poisson's effect, named after Simeon Poisson, a French mathematician and physicist.

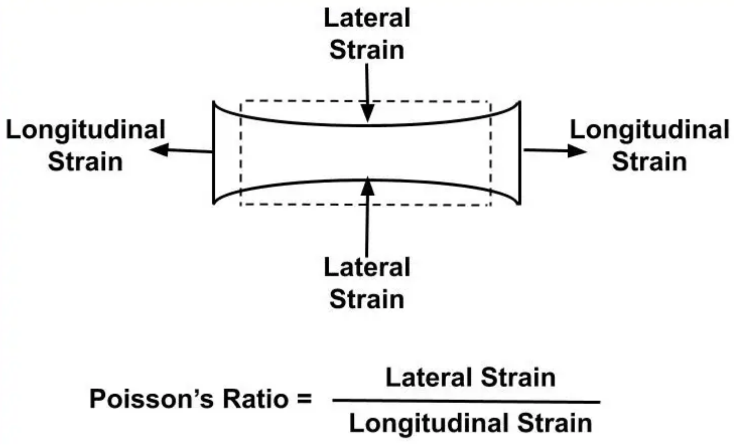


Figure 6: Poisson's ratio

Figure 6 shows *that Poisson's ratio* is defined as the ratio of the transverse strain to the axial strain under the same force and is a constant material property. As such, when a force is applied to a bar, it causes axial and transverse deformation, and Poisson's ratio relates these changes. The greater the Poisson's ratio value, the more rigid a plate will be, and its capacity to tolerate stress increases.

Tensile strength

Geologically, "tension" is a type of stress that causes rocks to stretch in opposite directions, and this stretching causes the rocks to become longer laterally and thinner vertically. A significant outcome of tensile stress is jointing, which involves the formation of fractures or cracks in rocks due to the stretching forces acting upon them.

3.4 Development of Numerical Models

3.4.1. Room and Pillar design

During my study, models were developed using FLAC3D, a structural analysis software developed by the Itasca Consultant Group. FLAC3D is based on finite differences and is used extensively for geotechnical modeling of geologic problems that involve highly complex geometries and linear and non-linear behavior.

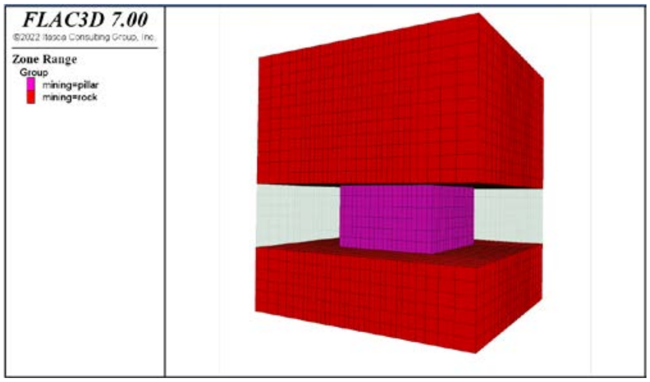


Figure 7: Single pillar

Initially, I used the FLAC3D zone create brick command to design a single pillar, and as I reflected more and more.

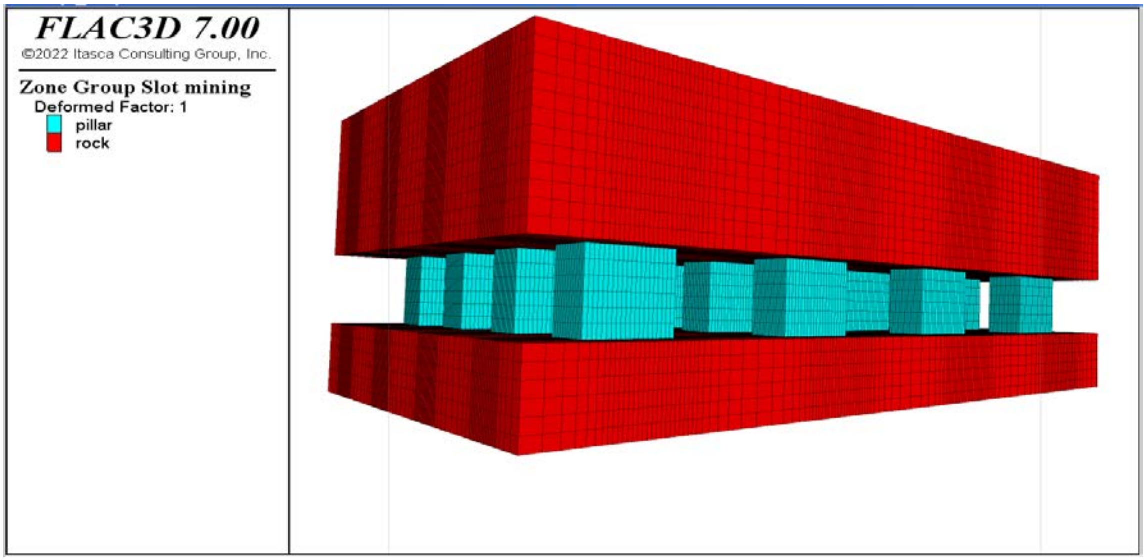


Figure 8: Room and pillar mining model

3.4.2 Boundary Condition

The values of field variables (such as stress and displacement) prescribed at the boundary of the numerical grid are the boundary conditions in a numerical model. There are two types of Boundaries which are real and artificial. The real boundaries are present in the physical object being modeled (surface and underground mines). On the other hand, artificial boundaries do not exist reality, but are introduced to enclose the desired number of zones.

There are two primary categories of mechanical boundary conditions: prescribed displacement and prescribed stress. An unconstrained surface is an exception to the prescribed-stress boundary. The two categories of mechanical conditions are described in Stress Boundary and Displacement Boundary.

Stress Boundary

Generally, the boundaries of a FLAC3D grid are stress-free and unrestricted. The zone face apply command can apply forces or stresses to any boundary or part of the boundary.

```
zone initialize-stresses ratio 0.25 0.5 overburden -1e6
zone face apply stress-zz -1e6
```

As you can observe, this is the stress boundary on my model.

Displacement Boundary

In FLAC3D, displacements cannot be directly controlled; they play no role in the calculation process. To apply a given displacement to a boundary, it is necessary to specify the boundary's velocity for a set number of steps.

Zone-face or zone-gridpoint commands apply velocity conditions to gridpoints. Zone-face instructions select all connected gridpoints.

```
zone face skin
zone gridpoint fix velocity-x range group 'skin=west'  or 'skin=east'
zone gridpoint fix velocity-y range group 'skin=south' or 'skin=north'
zone gridpoint fix velocity-z range group 'skin=bottom'
```

This are my displacement boundary conditions on my model, fixing the normal displacements to zero at the sides and the bottom of the model.

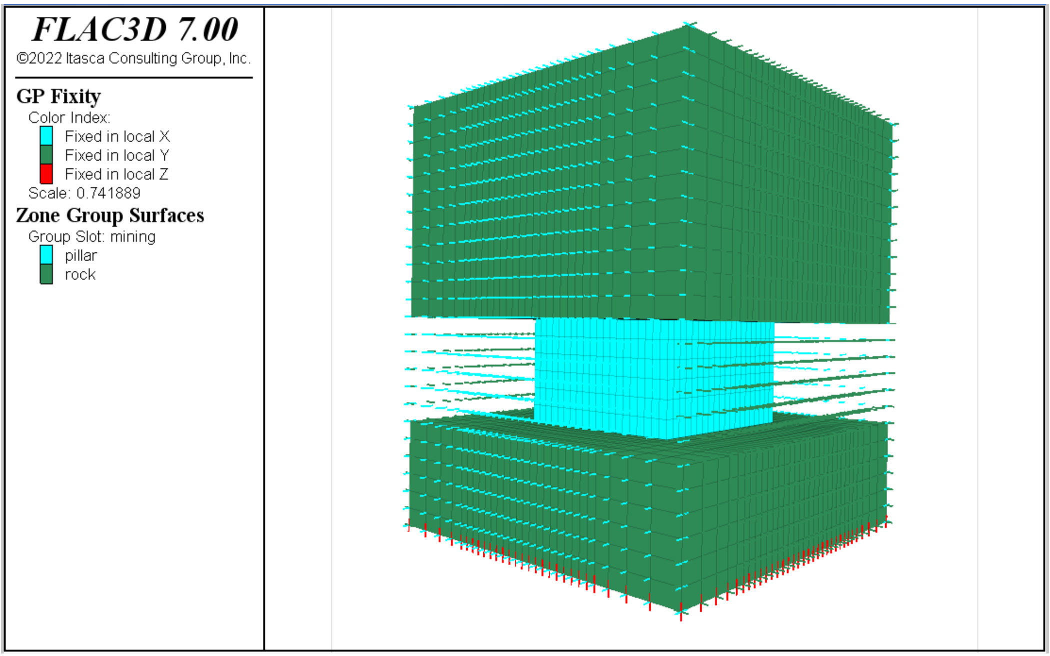


Figure 9: Single pillar with displacement boundary

3.4.3 Material strength parameter

I researched soft rock's characteristics by reviewing books, articles, and the FLAC3D 7.0 software manual. Following that, I selected geological properties comparable to those of weak rock, and these simulations were based on this property. I utilized three distinct geological formations in my thesis, but both had nearly identical weak rock characteristics.

Geology	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	2.00E+09	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	1.50E+09	0.32	0.60E+06	45.6	1.00E+05
Rock 3	2000	1.30E+09	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	1.50E+09	0.22	1.00E+06	25	1.00E+05

Table 4: Strength parameter 1

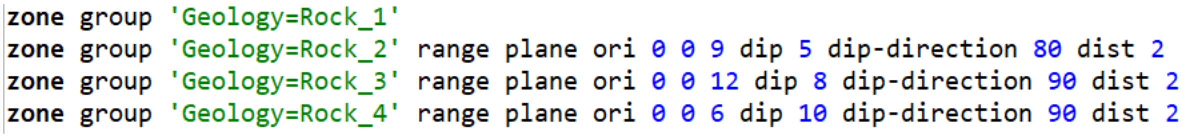
Geology	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	1.00E+09	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	0.50E+09	0.32	1.60E+06	45.6	1.00E+06
Rock 3	2000	0.30E+09	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	0.50E+09	0.22	1.00E+06	25	1.00E+05

Table 5: Strength parameter 2

Geology	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	2.00E+08	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	1.50E+08	0.32	1.60E+06	45.6	1.00E+06
Rock 3	2000	1.30E+08	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	1.50E+08	0.30	1.00E+06	25	1.00E+05

Table 6: Strength parameter 3

The formation of rocks results from various geological processes, such as volcanic activity or sedimentation. These processes are typically localized and can lead to the concentration of comparable rocks in one place. Therefore, geological formations are frequently composed of rocks with similar properties, producing a distinctive landscape unique to a region. In my research, I included four different rocks, each of which had properties that were similar to each other.



```
zone group 'Geology=Rock_1'
zone group 'Geology=Rock_2' range plane ori 0 0 9 dip 5 dip-direction 80 dist 2
zone group 'Geology=Rock_3' range plane ori 0 0 12 dip 8 dip-direction 90 dist 2
zone group 'Geology=Rock_4' range plane ori 0 0 6 dip 10 dip-direction 90 dist 2
```

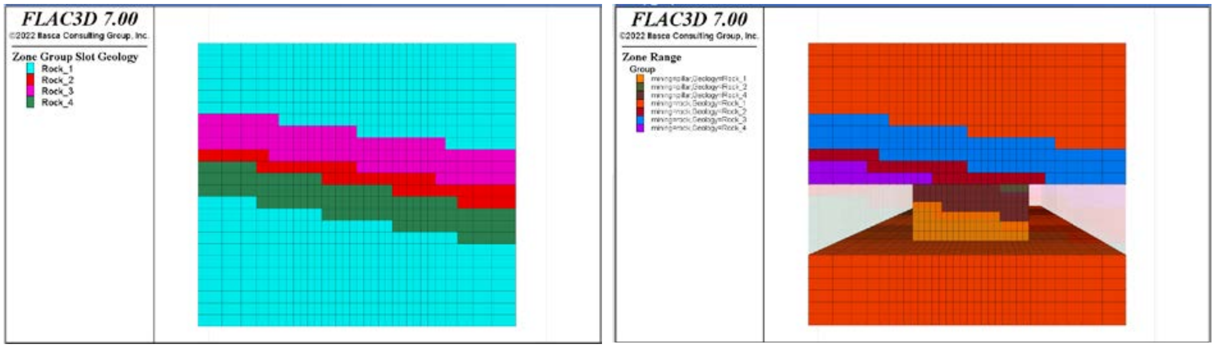


Figure 10: Geological layer on model

4. Case study, Analysis, Experiments

4.1 Simulation of room and pillar mining

My simulation would be based on weak rock conditions and try to define the dimension based on the safety and economic. The strength parameters of construction materials are crucial in designing and building safe and stable structures. Structural elements like pillars carry heavy loads, and ensuring that the materials used in their construction can handle the weight is important. When a material has good strength parameters, it is possible to make narrower pillars, which save space and have aesthetic advantages.

On the other hand, when the strength parameters of a material are inadequate, wider pillars are necessary to ensure stability and safety. Wider pillars take up more space and can have aesthetic drawbacks that can impact the structure's overall design. To mitigate this, backfill material can fill the space around the pillar and distribute the load more evenly across the foundation. Backfill material also provides additional support to prevent the pillar from undergoing deformation or failure.

During my study, I simulate room and pillar mining by defining material strength, dimension, and varied sizes, and backfill heights.
There are:

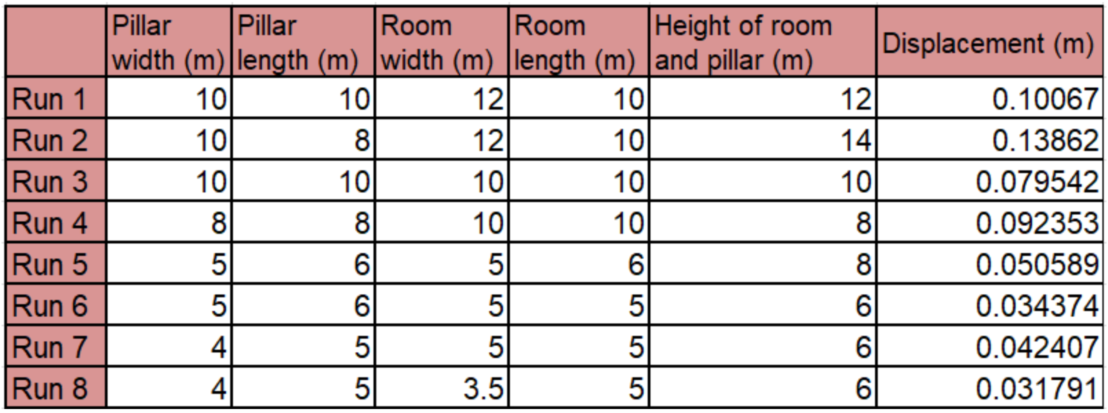
- Optimize the room and pillar
    a. Pillar sizes (Width, Length, Height)
    b. Room sizes (Width, Length, Height)
    c. Strength parameters (Density, Young’s Modulus, Cohesion, Friction angle, Poisson’s ratio, Tensile strength)
- Backfill
    a. Backfill material Height

On the other hand, Boundary conditions and geological layers are would be constant.

4.1.1 Dimension of room and pillar

According to the geological property, rock formation, as well as the boundary conditions, are always the same. I replicate the different sizes of the pillars and the rooms. When I was mining for rooms and pillars, I came across a stable pillar.

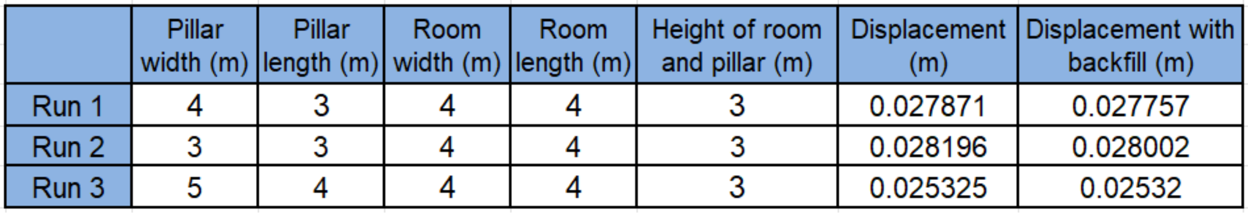
Geology	Density (kg/m^3)	Young’s Modulus (GPa)	Poisson’s Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	2.00E+09	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	1.50E+09	0.32	0.60E+06	45.6	1.00E+05
Rock 3	2000	1.30E+09	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	1.50E+09	0.22	1.00E+06	25	1.00E+05



	Pillar width (m)	Pillar length (m)	Room width (m)	Room length (m)	Height of room and pillar (m)	Displacement (m)
Run 1	10	10	12	10	12	0.10067
Run 2	10	8	12	10	14	0.13862
Run 3	10	10	10	10	10	0.079542
Run 4	8	8	10	10	8	0.092353
Run 5	5	6	5	6	8	0.050589
Run 6	5	6	5	5	6	0.034374
Run 7	4	5	5	5	6	0.042407
Run 8	4	5	3.5	5	6	0.031791

Table 7: Different sizes of room and pillar with displacement

The following table 7 illustrates the relationship between the pillars' stability and the mining region's geology and size. I first put similar dimensions of the room and pillar. Therefore, I obtained large sizes of rooms and pillars; for example, run 1 has big pillars and rooms and has lower strength and higher displacement values. On the other hand, small sizes of pillars and rooms have high strength and low displacement value. As you can see from the table above, the smaller pillars and rooms had less displacement and more strength, so I kept the size of the room unchanged and only changed the length and width of the pillar.



	Pillar width (m)	Pillar length (m)	Room width (m)	Room length (m)	Height of room and pillar (m)	Displacement (m)	Displacement with backfill (m)
Run 1	4	3	4	4	3	0.027871	0.027757
Run 2	3	3	4	4	3	0.028196	0.028002
Run 3	5	4	4	4	3	0.025325	0.02532

Table 8: Different sizes of room and pillar, displacement with backfill and without

While conducting my simulation, I noticed that smaller pillar and room sizes resulted in higher strength and lower displacement.

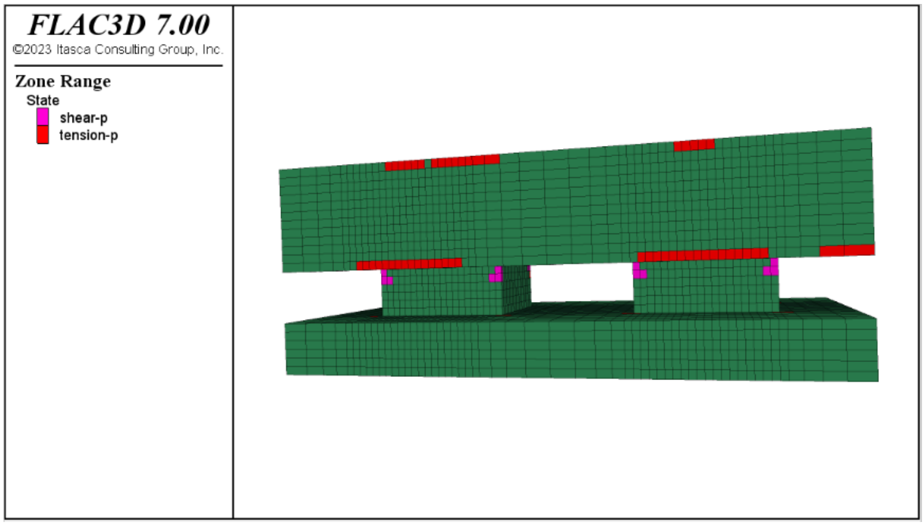


Figure 11: Small sizes of room and pillar, pillar state

The area's state was more stable than large sizes with a vertical displacement of around 2.7cm, indicating no need for backfill material. According to the table, there is little change in displacement and the area's state, thus making backfill material unnecessary.

As a result, larger pillars and rooms had a higher displacement and lesser strength, which meant that the states of the pillars would be unstable.

Geology	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	1.00E+09	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	0.50E+09	0.32	1.60E+06	45.6	1.00E+06
Rock 3	2000	0.30E+09	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	0.50E+09	0.22	1.00E+06	25	1.00E+05

Backfilling enhances stability and safety in room-and-pillar mining, particularly in the presence of unstable rock. Utilizing the proper backfilling materials allows for more cost-effective and secure mining operations. To better understand the effects of backfilling on pillar stability, data were collected from large rooms and pillar structures, with a concentration on assessing the potential for pillar displacement and instability in geologies with reduced strength.

	Pillar width (m)	Pillar length (m)	Room width (m)	Room length (m)	Height of room and pillar (m)	Displacement (m)
Run 1	10	10	12	10	12	0.27033
Run 2	10	8	12	10	12	0.37619
Run 3	8	8	12	10	12	1.1362
Run 4	10	8	12	10	14	0.47088
Run 5	8	8	12	10	10	0.75583
Run 6	9	8	12	10	10	0.39918

Table 9: Different size of room and pillar with displacement

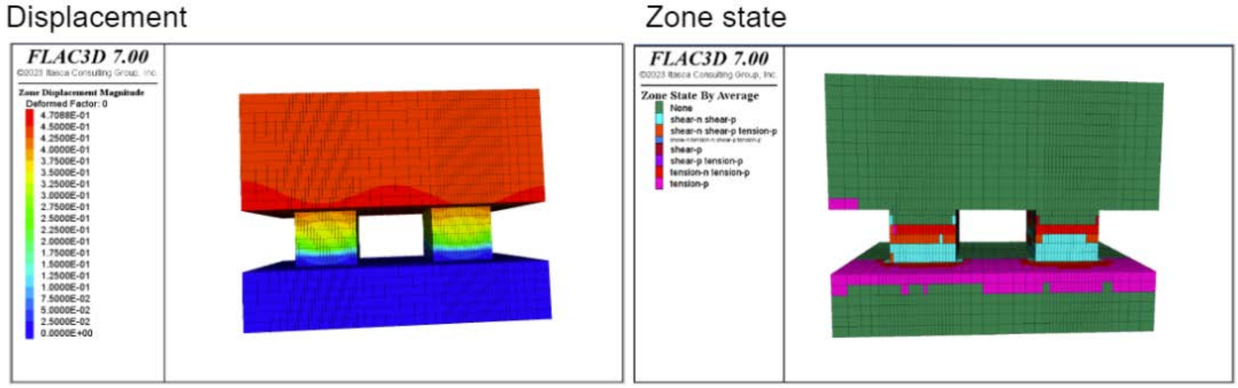


Figure 12: Displacement and Zone state on pillar

Displacement is a crucial parameter in FLAC3D for analyzing the behavior of geological materials, particularly under loading or mining conditions. During mining or excavation, the displacement analysis in FLAC3D involves anticipating the movement and deformation of the rock mass.

As a result of loading or mining, the rock mass endures deformation and movement. This movement can cause the rock mass to become unstable, leading to structural failure or catastrophe. By simulating the displacement of the granite mass under various loading or mining conditions, engineers can evaluate the system's stability and identify potential issues such as roof collapse or pillar failure.

State of pillars entails assessing the strength and stability of rock pillars, identifying failure mechanisms, and optimizing the mining process for safety and productivity. The combination of displacement and state of pillar analyses allows the evaluation of design parameters, such as pillar size and spacing, to optimize the mining process for optimum safety and productivity.

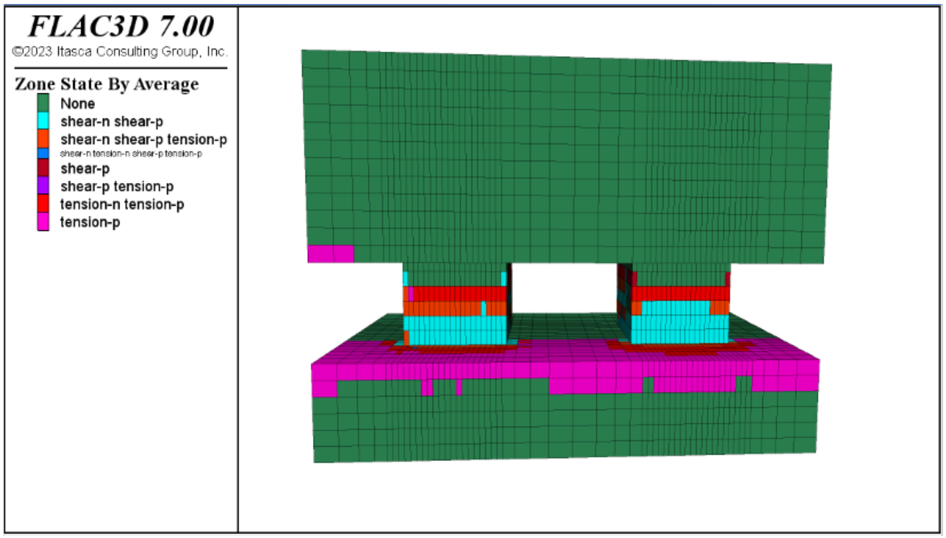


Figure 13: Pillar state on run 4

The data shown in the previous table demonstrate that the pillar and room sizes show a rather considerable vertical displacement at the strength parameter 2, and the pillar looks to be unstable and displacement is high in this figure. When a pillar fails, the surrounding area can collapse, risking the safety of workers and possibly causing damage to equipment and infrastructure. Backfilling can be used to increase the pillars' strength and stability to reduce the risk of pillar failure. Backfilling entails filling the mined-out areas with suitable material, such as refuse rock or cemented tailings, to provide additional support for the pillars. Moreover, the backfill material can redistribute the stress in the adjacent rock, decreasing the likelihood of pillar failure.

Geology	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Rock 1	1500	2.00E+08	0.28	3.00E+06	40	1.00E+06
Rock 2	1300	1.50E+08	0.32	1.60E+06	45.6	1.00E+06
Rock 3	2000	1.30E+08	0.25	2.60E+06	37	2.00E+06
Rock 4	2100	1.50E+08	0.30	1.00E+06	25	1.00E+05

	Pillar width (m)	Pillar length (m)	Room width (m)	Room length (m)	Height of room and pillar (m)
Run 1	4	4	6	6	6
Run 2	5	4	6	6	6
Run 3	5	5	6	6	6

Table 10: Different dimension of room and pillar

When the objective is to attain a medium size for the rooms and pillars, the larger room sizes pose a risk of instability. When rooms are more significant than the pillars, pillar failure is likely due to the additional weight and stress imposed on them. This risk, however, can be mitigated through the use of backfill material. Backfill material can assist in stabilizing the pillars and uniformly distributing the weight across the foundation, thereby reducing the risk of foundation failure.

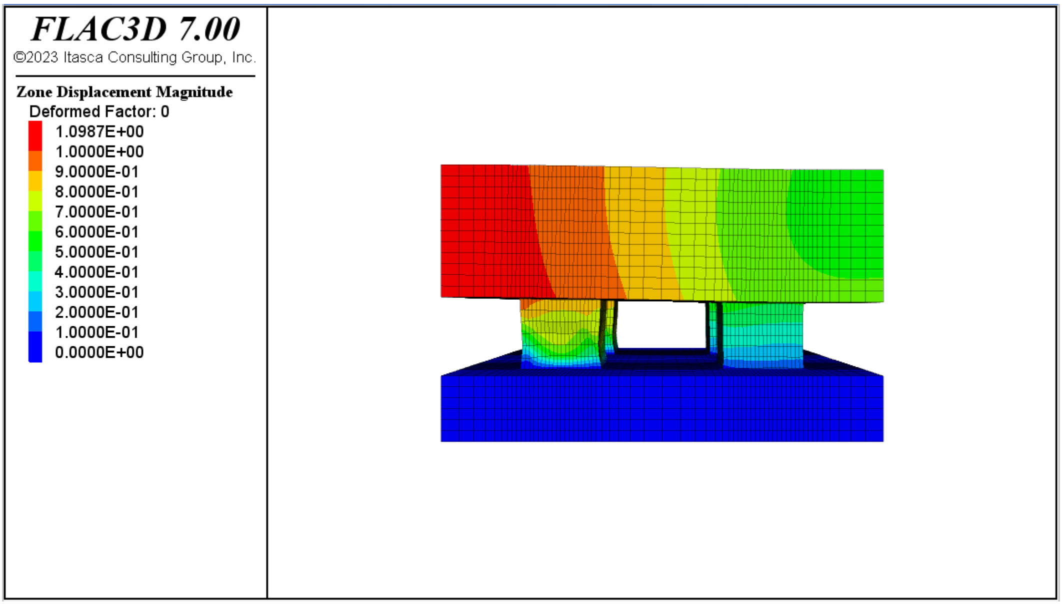
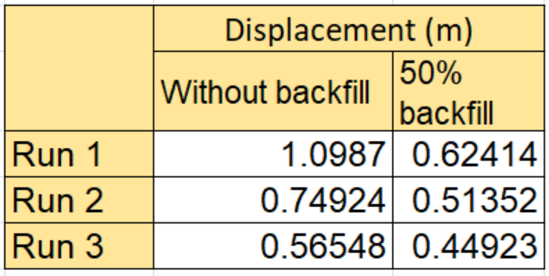


Figure 14: Pillar stability with displacement

By strengthening and stabilizing the pillars through backfilling, mining operations can be conducted more efficiently and safely. To ensure that the backfill is efficient and cost-effective, selecting the appropriate backfill materials and optimizing the mining dimensions is crucial to select the proper backfill materials and optimize the mining dimensions.



	Displacement (m)	
	Without backfill	50% backfill
Run 1	1.0987	0.62414
Run 2	0.74924	0.51352
Run 3	0.56548	0.44923

Table 11: Displacement compared backfilling on strength parameter 3

In a model with high displacement and unstable pillars, it is necessary to discover structural stabilization methods. This can be accomplished through the use of backfilling material. Filling the voids around the pillars with a suitable material can enhance the structure's load distribution, resulting in greater stability.

Referring to a table detailing the effects of backfill material, it can be seen that after backfilling, the structure's displacement has diminished by fifty percent. This indicates that the backfill material effectively supported the structure's weight and prevented significant deformation or failure. The use of backfill material serves to stabilize the pillars in addition to reducing displacement. This is because the material provides additional support, which aids in evenly distributing the burden across the foundation, thereby reducing the risk of pillar failure.

4.1.3 Backfilling

The backfill material can also serve as a working platform or a base for future mining activities. Backfilling can sometimes be combined with cement or other materials to create a more stable and durable support structure.
Backfilling materials can be classified into two main groups:

Sources of waste:

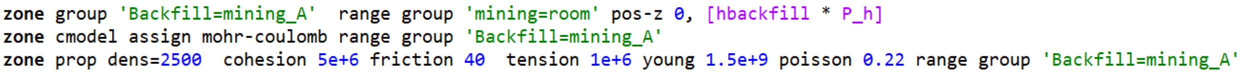
- Own waste (tailings, overburden, development waste)
- Outside waste (rock and aggregates of the construction industry, natural sands)

Binder:

- Cement (OPC)

- Portland cement: hydraulic cement because it sets and hardens by reacting chemically with water.
- General cement is vulnerable to chemical attack whenever backfill high in sulfites occurs.
- Fly ash
- Slag
- Gypsum
- (Ground waste glass)

Mine backfilling can be accomplished using different methods, including Dry/Rock fill, Hydraulic fill, and Paste fill. Dry or rock fill involves placing rock waste directly into the mined-out area, while hydraulic fill uses a slurry of tailings and water to fill the void. Paste fill is a mixture of tailings and cement or other binders to form a paste-like material. These backfilling methods are chosen based on the type of mine, the surrounding rock's characteristics, and the mining operation's specific needs.



```
zone group 'Backfill=mining_A'  range group 'mining=room' pos-z 0, [hbackfill * P_h]
zone cmodel assign mohr-coulomb range group 'Backfill=mining_A'
zone prop dens=2500  cohesion 5e+6 friction 40  tension 1e+6 young 1.5e+9 poisson 0.22 range group 'Backfill=mining_A'
```

The applying of high-strength filling materials to induce high restraint stresses is known as increasing the strength of the pillar. Given the weak nature of the geological conditions, we could use more high-strength materials, which can be selected based on their economic viability and safety considerations. On my model, I used hard backfill material, like a hydraulic cement because it sets and hardens by reacting chemically with water. To ensure the stability of the pillar, it was backfilled with suitable materials. Various heights and strength parameters of backfill materials were investigated and compared to the pillar's 30%, 50%, and 70% heights.

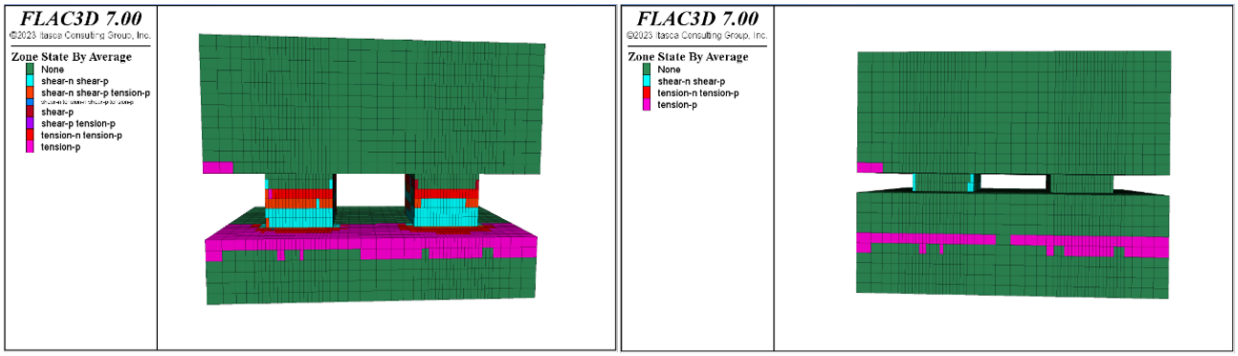
	Density (kg/m^3)	Young's Modulus (Mpa)	Poisson's Ratio (-)	Cohesion (MPa)	Friction angle (Degree)	Tension
Backfill material 1	2500	1.5e+9	0.22	5e+6	40	1e+6

Table 12: Backfill material strength parameter

	Displacement (m)			
	No backfill	Height 30%	Height 50%	Height 70%
Run 1	0.27033	0.24819	0.24479	0.24109
Run 2	0.37619	0.30521	0.2949	0.28546
Run 3	1.1362	0.39908	0.37613	0.35648
Run 4	0.47088	0.30582	0.29277	0.28208
Run 5	0.75583	0.39328	0.38257	0.3717
Run 6	0.39918	0.3218	0.31667	0.30992

Table 13: Comparing different heights of backfill

The table provides information on the displacement changes observed after the backfilling process. To compare the effects of backfilling, I analyzed the displacement values without any backfilling and compared them to the displacement values achieved, with 70% of the pillar height being backfilled. It was observed that the pillar strength increased as the backfilling height increased. However, in some cases, backfilling heights of 30% and 50% did not cause significant changes in displacement. This suggests that backfilling heights of 30% may be sufficient. It is important to consider this information as unnecessary backfilling could result in material and machine costs without significant improvement in stability.



No backfill

70% Backfill

Figure 15: Stability of pillar, compared different height of backfill on run 4

The figure presented above shows that the stability of the pillars can be improved. This figure is example of backfilling, which is run 4. Based on my simulation with backfill material, I have found that the strength of weak rock condition pillars increases gradually as the backfill body height increases. Specifically, I have observed that filling 30% of the pillar height with backfill material yields a lower strength increase compared to filling 70% of the pillar height. Additionally, I have found that the pillar strength is at its highest when the backfill body height equals the pillar height. This suggests that if you first determine the appropriate pillar size for weak rock geology, you can adjust the size slightly to optimize the strength of the pillar.

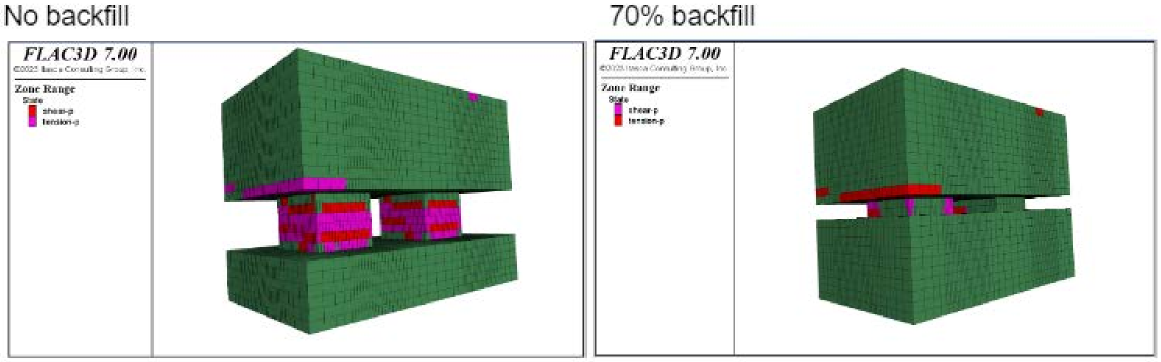


Figure 16: Stability of pillar, compared different height of backfill

By referring to this figure, it is evident that the pillars have been stabilized. The values for shear strength (p) and tension strength (p) are lower than those after the backfill.

4.2 Direction of excavation sequence

I try to did the room and pillar mining scheme, which I determine the extracted sequence of reliable. In weak rock conditions, the direction of excavation in room-and-pillar mining is typically selected to minimize the risk of roof collapse and preserve the stability of the pillars. I researched on the direction of excavation and little simulation on the room and pillar mining. Then I learned that horizontal excavation is frequently preferred to vertical excavation because it provides more support for the roof and reduces the weight of the overlying rock.

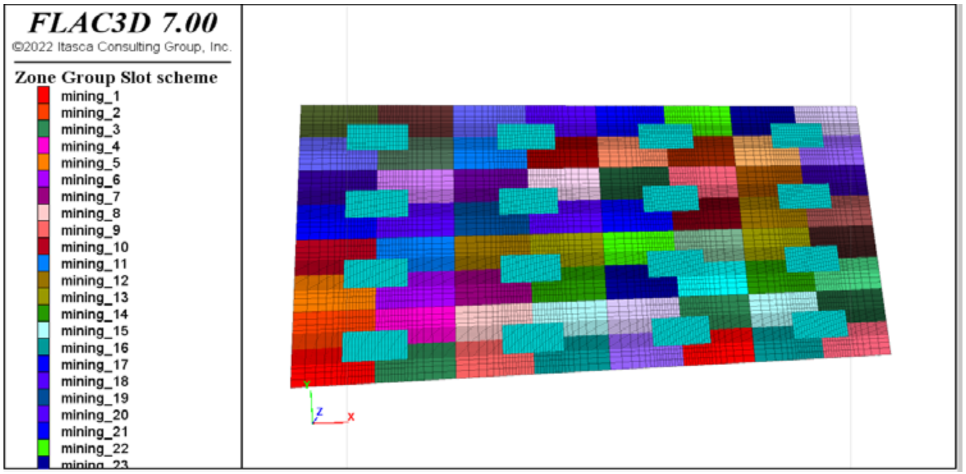


Figure 17: Room and Pillar mining design

In unstable rock conditions, horizontal excavation is frequently preferred to vertical excavation in room-and-pillar mining because it provides more support for the roof and reduces the weight of the rock above. This reduces the risk of roof collapse and maintains the pillars' stability. Typically, the excavated area is divided into parallel rooms and pillars, with rectangular rooms that are connected by corridors or entrances.

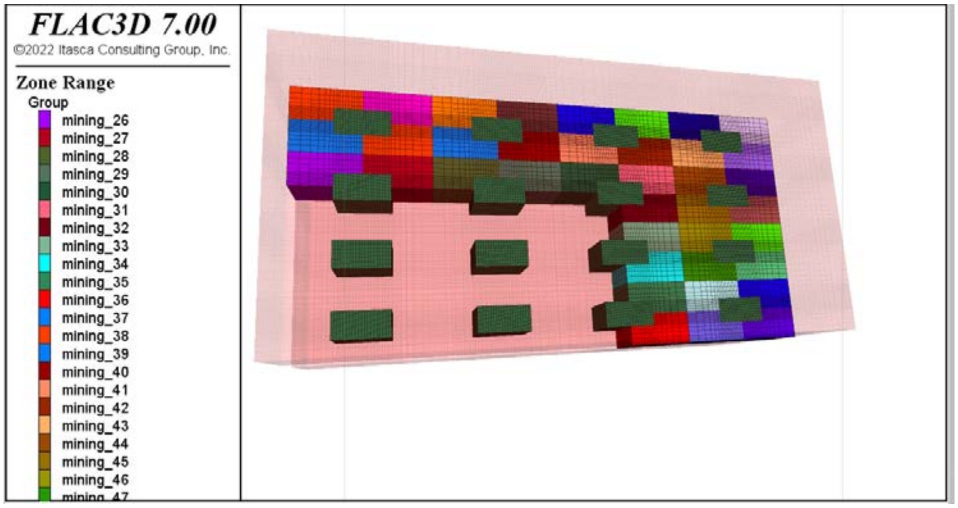


Figure 18: Room and pillar mining design with excavation

In addition to proper excavation methods, backfilling can play a crucial role in assuring a mine's safety and economic viability. By covering the space near the mining operation with suitable material, backfilling can increase the mine's overall stability and support the remaining pillars, thereby decreasing the risk of roof collapse. This can increase worker safety, reduce delays caused by instability or collapse, and lengthen the mine's lifespan.

5. Result / Discussion

5.1 Economic and safety aspect

In weak rock conditions, optimizing the design of the pillars and rooms to ensure optimum safety and productivity presents numerous challenges. Profitability is crucial for any mining operation, and optimizing the design of the pillars is essential to achieving this objective.

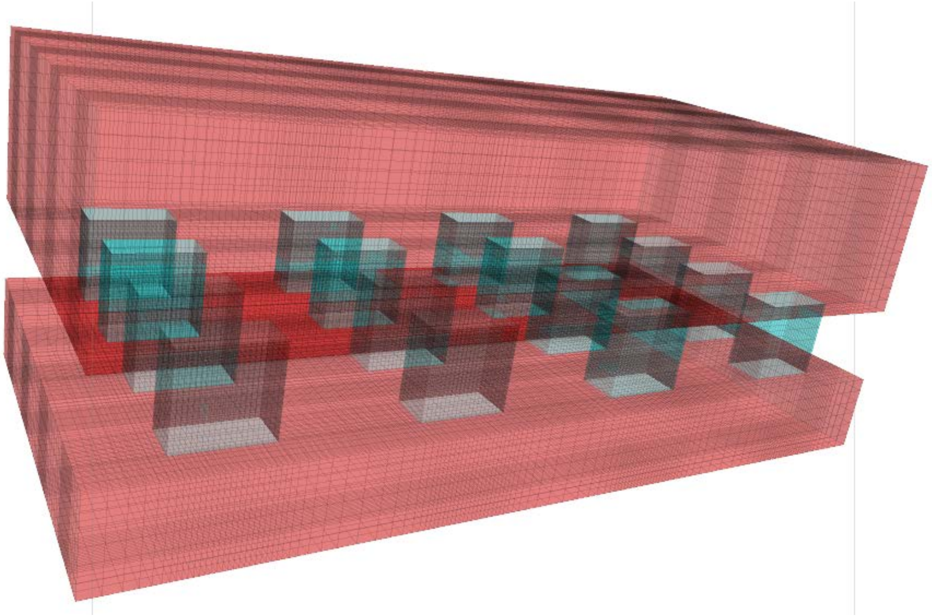


Figure 19: Room and pillar mining model

Optimizing the design of pillars and rooms involves prioritizing safety by employing larger pillars and confined rooms. This strategy can assure the mine's stability, but there may be more economically viable alternatives. Consequently, optimizing the limited pillars to extract efficiency and safety is an alternative strategy.

Engineers can achieve this objective by simulating the behavior of the granite mass under various loading conditions using sophisticated software tools such as FLAC3D. Using this software, they can evaluate design parameters such as pillar size, room dimensions, and backfill material to determine the safest and most efficient design. Optimizing the narrow pillars in conditions of weak granite requires a delicate balance between safety and productivity. Engineers must consider the geological conditions of the mine, the loading conditions, and the possibility of failure mechanisms such as shear, bending, or buckling. It is possible to balance safety, efficiency, and profitability in room-and-pillar mining on the weak rock through meticulous analysis and design optimization.

Based on the simulation results, smaller rooms and pillars tend to have higher strength and lower displacement values, which can be more economical. However, in practical mining operations, it can be challenging to accommodate small rooms due to the size of the mining equipment. Therefore, optimization of larger room and pillar sizes may be necessary. However, larger sizes can result in more displacement and loss of strength, which backfilling can mitigate.

Backfilling with high-strength material can help stabilize the pillars and reduce the required backfilling material. It is also essential to consider the height of the backfilling, as there may be more efficient options than using the same height as the pillar. The simulation showed that a 30% to 70% height of backfilling can sometimes result in negligible differences. Thus, using a 30% height of backfilling may be more efficient in certain situations. Optimizing the size and use of backfilling can help balance efficiency and safety in room and pillar mining operations in weak rock conditions.

In weak rock conditions, the direction of excavation in room-and-pillar mining is typically selected to minimize the risk of roof collapse and preserve the stability of the pillars. Then I learned that horizontal excavation is frequently preferred to vertical excavation because it provides more support for the roof and reduces the weight of the overlying rock. The rooms are typically rectangular and connected by corridors or entries. Backfilling the rooms at a small distance from the mining operation can have significant economic and safety benefits. When adequately executed, backfilling can improve the overall stability of the mine by supporting the remaining pillars and reducing the risk of roof collapse. This, in turn, can increase worker safety, reduce downtime due to instability or collapse, and extend the life of the mine.

5.2 Backfilling

In my research on room-and-pillar mining, I intend to evaluate the stability of pillars from both a safety and an economic standpoint by analyzing several strength parameters. I ran several numerical simulations with various strength parameters 3, one of which is depicted below. This model displays displacement and stability phases, visually representing how the pillars are stabilized in this case.

Run 5				
Pillar width (m)	Pillar length (m)	Room width (m)	Room length (m)	Height of room and pillar (m)
8	8	12	10	10

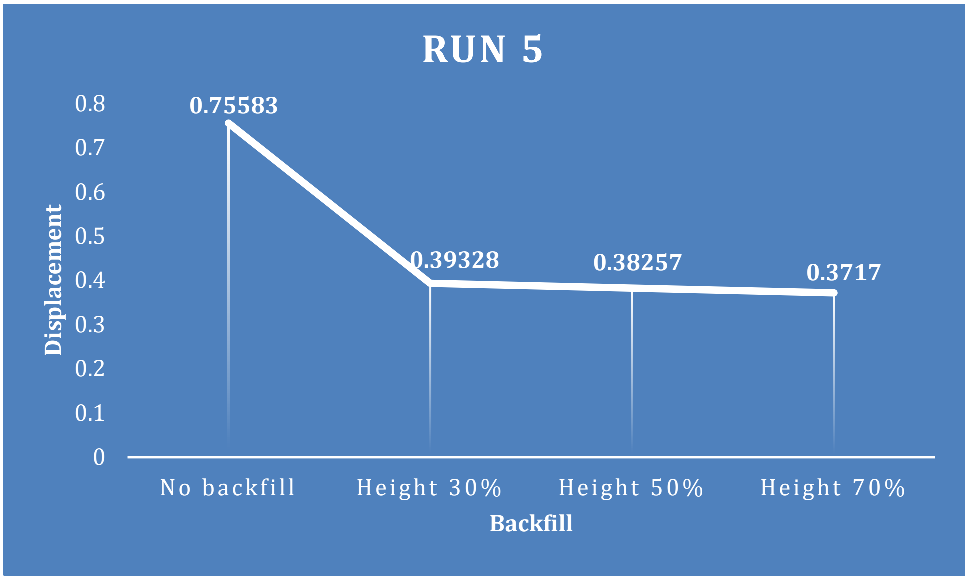


Figure 20: Graph on backfilling and displacement

Using high-strength material for backfilling can enhance pillar stability while reducing the required backfilling material. Furthermore, it is imperative to consider the height of the backfilling since using the same height as the pillar may only sometimes be the most efficient option. According to the simulation results, a height of backfilling ranging from 30%

to 70% of the pillar height can sometimes result in insignificant variations. Thus, in certain situations, a backfilling height of 30% may be more practical. Optimizing backfilling size and utilization makes it possible to strike a balance between safety and efficiency in room and pillar mining operations carried out under weak rock conditions.

6. Conclusion

In this paper, a comprehensive and detailed room and pillar mining model was developed to determine the optimal dimensions of rooms and pillars in weak rock geology. The study included three geology strength parameters, focusing on creating economically viable narrow pillars while incorporating backfill material for stability.

Through the analysis of the three different geological parameters, the study aimed to determine the support pillars required for high-strength parameters using backfill while considering economic and safety considerations. The findings of this study underscore the critical importance of conducting a thorough geological survey and performing geotechnical and geomechanical research and analysis using numerical modeling when calculating the mine design. Such research is crucial for ensuring safety and optimizing mining operations in weak rock conditions. As the mining industry continues to grow and expand, the results of this study can serve as a valuable foundation for future research and development in this field, ultimately leading to improvements in efficiency and safety.

In conclusion, this study has contributed significantly to shaping and advancing the future of mining engineering research and practice.

7. Recommendations/ further research

My study used a simulated geological formation and a hypothetical mining scenario. Further research can build on the findings of this study by analyzing real-world mining projects and exploring various mining methods. Future studies could focus on applying the findings of this study to actual mining operations and evaluating the effectiveness of different support measures. A detailed geological survey and rock testing could be conducted to determine the strength and stability of the rock mass, providing a more accurate assessment of pillar stability under different mining conditions.

Furthermore, other factors such as mining depth, ground stress, and groundwater conditions can significantly affect pillar stability. Future studies could investigate the impact of these factors on room and pillar mining in weak rock conditions.

In terms of support measures, further research can explore alternative reinforcement methods, such as bolting, shotcreting, or steel arches, may be necessary to reinforce the pillars and prevent collapse. Further research on room and pillar mining in weak rock conditions can enhance our understanding of the underlying geotechnical and geomechanical processes and develop more effective mining practices. This will improve the efficiency of mining operations and ensure the safety of mine workers.

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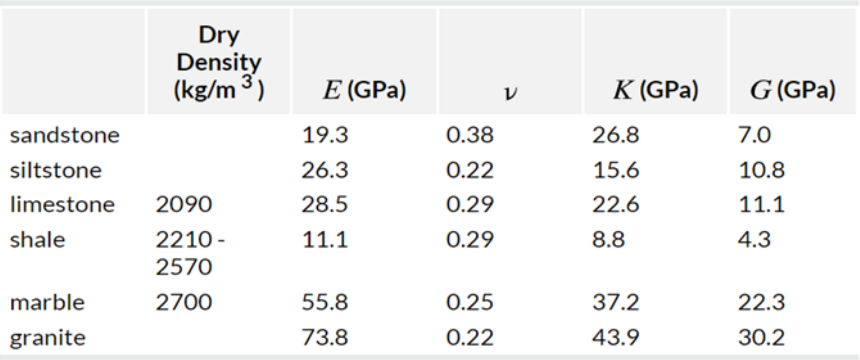
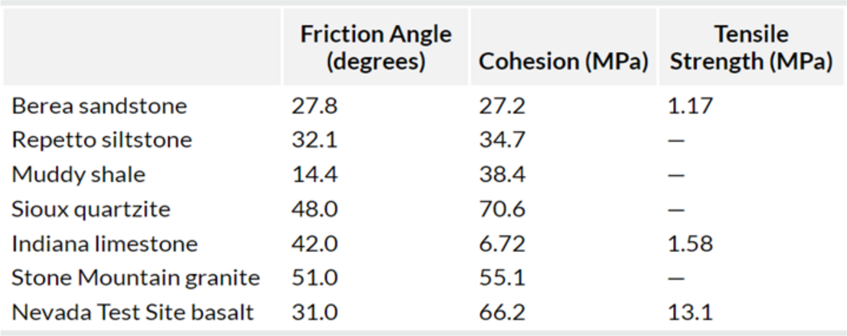
Appendix



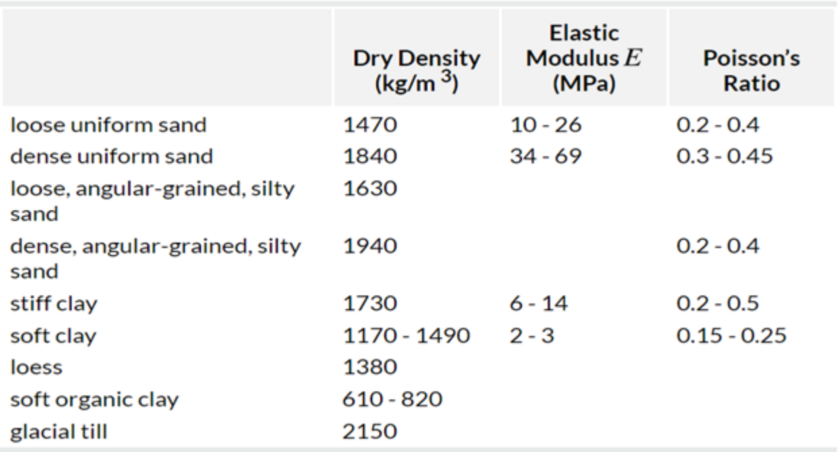
	Dry Density (kg/m^3)	E (GPa)	ν	K (GPa)	G (GPa)
sandstone		19.3	0.38	26.8	7.0
siltstone		26.3	0.22	15.6	10.8
limestone	2090	28.5	0.29	22.6	11.1
shale	2210 - 2570	11.1	0.29	8.8	4.3
marble	2700	55.8	0.25	37.2	22.3
granite		73.8	0.22	43.9	30.2

Table 14:Selected Elastic Constants(laboratory-scale) for Rocks (adapted from Goodman 1980)



	Friction Angle (degrees)	Cohesion (MPa)	Tensile Strength (MPa)
Berea sandstone	27.8	27.2	1.17
Repetto siltstone	32.1	34.7	—
Muddy shale	14.4	38.4	—
Sioux quartzite	48.0	70.6	—
Indiana limestone	42.0	6.72	1.58
Stone Mountain granite	51.0	55.1	—
Nevada Test Site basalt	31.0	66.2	13.1

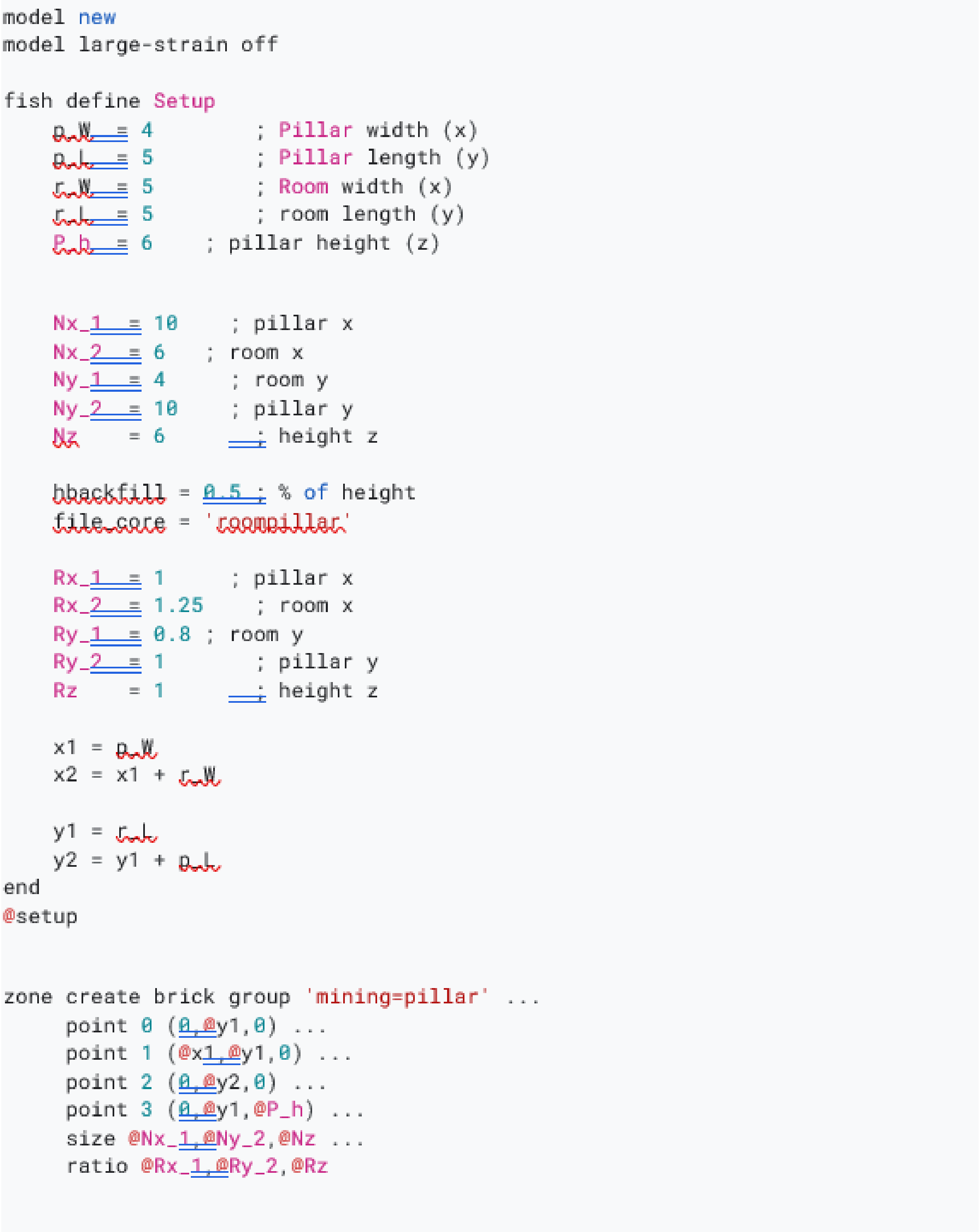
Table 15:Selected Strength Properties (Laboratory-scale) for Rocks (adapted from Goodman 1980)



	Dry Density (kg/m^3)	Elastic Modulus E (MPa)	Poisson's Ratio
loose uniform sand	1470	10 - 26	0.2 - 0.4
dense uniform sand	1840	34 - 69	0.3 - 0.45
loose, angular-grained, silty sand	1630		
dense, angular-grained, silty sand	1940		0.2 - 0.4
stiff clay	1730	6 - 14	0.2 - 0.5
soft clay	1170 - 1490	2 - 3	0.15 - 0.25
loess	1380		
soft organic clay	610 - 820		
glacial till	2150		

Table 16:Selected Elastic Constants (laboratory-scale) for Soils (Adapted from Das 1994)

On FLAC3D software, My simulation script of room and pillar mining



```
model new
model large-strain off

fish define Setup
    p_W  = 4        ; Pillar width (x)
    p_L  = 5        ; Pillar length (y)
    r_W  = 5        ; Room width (x)
    r_L  = 5        ; room length (y)
    P_h  = 6    ; pillar height (z)


    Nx_1  = 10    ; pillar x
    Nx_2  = 6   ; room x
    Ny_1  = 4     ; room y
    Ny_2  = 10    ; pillar y
    Nz    = 6       ; height z

    hbackfill = 0.5 ; % of height
    file_core = 'roompillar'

    Rx_1  = 1     ; pillar x
    Rx_2  = 1.25    ; room x
    Ry_1  = 0.8 ; room y
    Ry_2  = 1       ; pillar y
    Rz    = 1       ; height z

    x1 = p_W
    x2 = x1 + r_W

    y1 = r_L
    y2 = y1 + p_L
end
@setup


zone create brick group 'mining=pillar' ...
     point 0 (0,@y1,0) ...
     point 1 (@x1,@y1,0) ...
     point 2 (0,@y2,0) ...
     point 3 (0,@y1,@P_h) ...
     size @Nx_1,@Ny_2,@Nz ...
     ratio @Rx_1,@Ry_2,@Rz
```

```
zone create brick group 'mining=room'  ...
     point 0 (@x1,@y1,0) ...
     point 1 (@x2,@y1,0) ...
     point 2 (@x1,@y2,0) ...
     point 3 (@x1,@y1,@P_h) ...
     size @Nx_2,@Ny_2,@Nz ...
     ratio @Rx_2,@Ry_2,@Rz

zone create brick group 'mining=room' ...
     point 0 (0,0,0) ...
     point 1 (@x1,0,0) ...
     point 2 (0,@y1,0) ...
     point 3 (0,0,@P_h) ...
     size @Nx_1,@Ny_1,@Nz ...
     ratio @Rx_1,@Ry_1,@Rz

zone create brick group 'mining=room'  ...
     point 0 (@x1,0,0) ...
     point 1 (@x2,0,0) ...
     point 2 (@x1,@y1,0) ...
     point 3 (@x1,0,@P_h) ...
     size @Nx_2,@Ny_1,@Nz ...
     ratio @Rx_2,@Ry_1,@Rz

zone reflect origin 0,0, 0 norm 0,0,-1
zone reflect origin 0,0,[P_h] norm 0,0, 1

zone group 'mining=rock' range pos-z -100 0
zone group 'mining=rock' range pos-z [P_h] 100


zone reflect ori 0 0 0 norm -1 0 0
zone reflect ori 0 [P_L+R_L]  0 norm 0 1 0
zone reflect ori 0 [2*(P_L+R_L)]  0 norm 0 1 0
;zone reflect ori 0 [4*(P_L+R_L)]  0 norm 0 1 0
;zone reflect ori 0 [8*(P_L+R_L)]  0 norm 0 1 0

zone reflect ori [P_W+R_W] 0 0 norm 1 0 0
;zone reflect ori 0 0 [-P_H]  norm 0 0 -1
;zone delete range pos-z -10000 [-2*P_H]
```

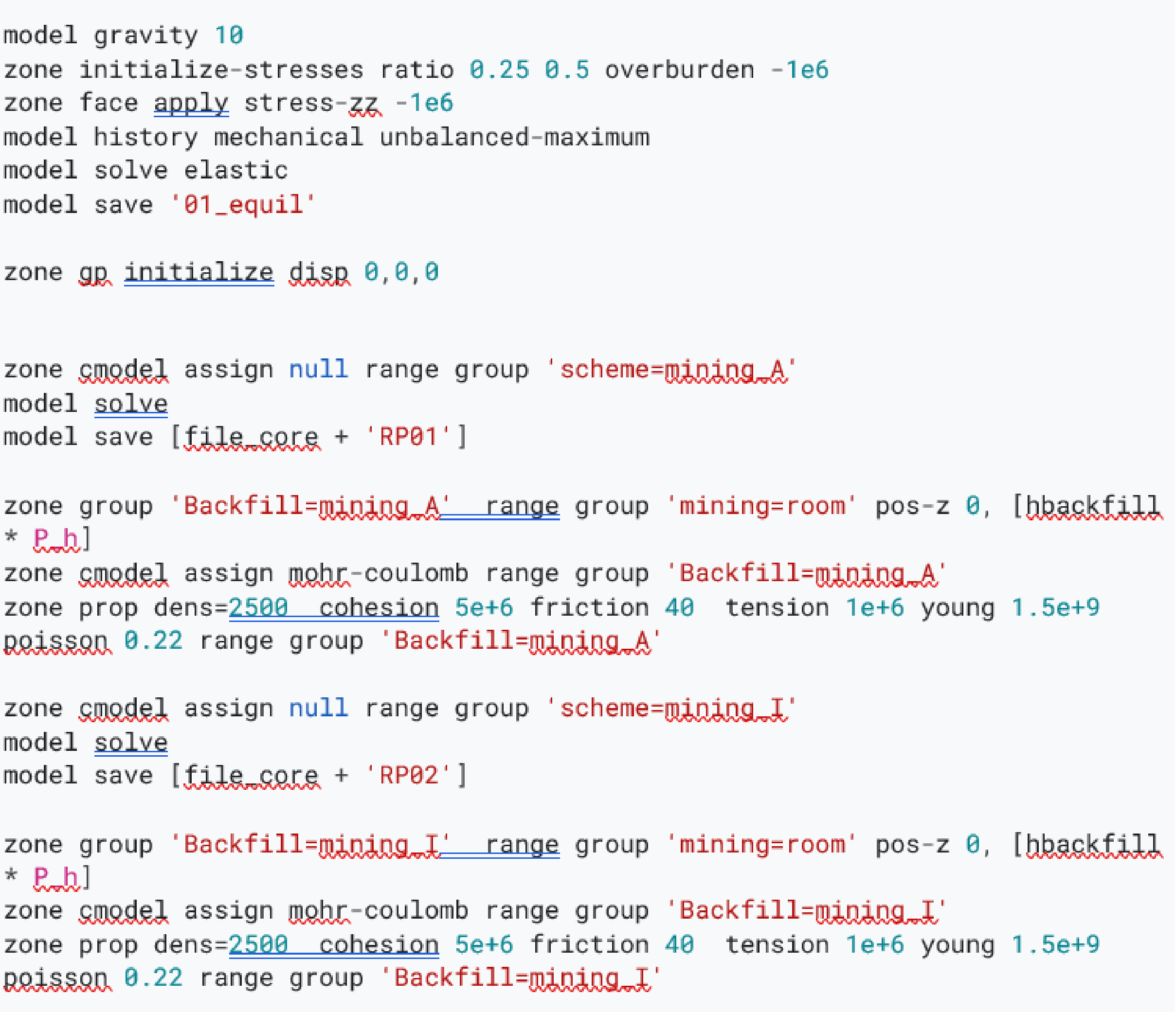
```
zone group 'Geology=Rock_1'
zone group 'Geology=Rock_2' range plane ori 0 0 7 dip 5 dip-direction 80 dist
2
zone group 'Geology=Rock_3' range plane ori 0 0 5 dip 8 dip-direction 90 dist
2
zone group 'Geology=Rock_4' range plane ori 0 0 2 dip 10 dip-direction 90
dist 2

zone group 'scheme=pillar'    range group 'mining=pillar'
zone group 'scheme=mining_A'  range group 'mining=room'  pos-x [-P_W-R_W]
0    pos-y 0                  [1*(P_L+R_L)]
zone group 'scheme=mining_A'  range group 'mining=room'  pos-x [-P_W-R_W]
0    pos-y [1*(P_L+R_L)]      [2*(P_L+R_L)]
zone group 'scheme=mining_A'  range group 'mining=room'  pos-x 0
[1*(P_W+R_W)]     pos-y 0                  [1*(P_L+R_L)]
zone group 'scheme=mining_A'  range group 'mining=room'  pos-x 0
[1*(P_W+R_W)]     pos-y [1*(P_L+R_L)]      [2*(P_L+R_L)]

zone group 'scheme=mining_I'  range group 'mining=room'  pos-x [-P_W-R_W]
0    pos-y [2*(P_L+R_L)]      [3*(P_L+R_L)]
zone group 'scheme=mining_I'  range group 'mining=room'  pos-x [-P_W-R_W]
0    pos-y [3*(P_L+R_L)]      [4*(P_L+R_L)]
zone group 'scheme=mining_I'  range group 'mining=room'  pos-x 0
[1*(P_W+R_W)]     pos-y [2*(P_L+R_L)]      [3*(P_L+R_L)]
zone group 'scheme=mining_I'  range group 'mining=room'  pos-x 0
[1*(P_W+R_W)]     pos-y [3*(P_L+R_L)]      [4*(P_L+R_L)]

zone cmodel assign mohr-coulom
zone prop dens=1500  cohesion 3e+6 friction 40   tension 1e+6 young 2e+8
poisson 0.28 range group 'geology=rock_1'
zone prop dens=1300  cohesion 1.6e+6 friction 45.6   tension 1e+6 young
1.5e+8 poisson 0.32 range group 'geology=rock_2'
zone prop dens=1400  cohesion 2.6e+6 friction 37   tension 2e+6 young 1.3e+8
poisson 0.25 range group 'geology=rock_3'
zone prop dens=1100  cohesion 1e+6 friction 25 tension 1e+5 young 1.5e+8
poisson 0.30 range group 'geology=rock_4'

zone face skin
zone gridpoint fix velocity-x range group 'skin=west'  or 'skin=east'
zone gridpoint fix velocity-y range group 'skin=south' or 'skin=north'
zone gridpoint fix velocity-z range group 'skin=bottom'
```



```
model gravity 10
zone initialize-stresses ratio 0.25 0.5 overburden -1e6
zone face apply stress-zz -1e6
model history mechanical unbalanced-maximum
model solve elastic
model save '01_equil'

zone gp initialize disp 0,0,0


zone cmodel assign null range group 'scheme=mining_A'
model solve
model save [file_core + 'RP01']

zone group 'Backfill=mining_A'  range group 'mining=room' pos-z 0, [hbackfill
* P_h]
zone cmodel assign mohr-coulomb range group 'Backfill=mining_A'
zone prop dens=2500  cohesion 5e+6 friction 40  tension 1e+6 young 1.5e+9
poisson 0.22 range group 'Backfill=mining_A'

zone cmodel assign null range group 'scheme=mining_I'
model solve
model save [file_core + 'RP02']

zone group 'Backfill=mining_I'  range group 'mining=room' pos-z 0, [hbackfill
* P_h]
zone cmodel assign mohr-coulomb range group 'Backfill=mining_I'
zone prop dens=2500  cohesion 5e+6 friction 40  tension 1e+6 young 1.5e+9
poisson 0.22 range group 'Backfill=mining_I'
```